IDEA DETECTOR CONCEPT

PATRIZIA AZZI - INFN-PD

For the RD-FCC INFN IDEA R&D Effort

Many thanks to my colleagues for the material:

F. Bedeschi, N. De Filippis, G. Gaudio, P. Giacomelli, M. Lucchini, F. Palla, I. Vivarelli, etc.etc.

NEXT COLLIDER, FCC-ee

- **Physics goals:**
  - **Massively improve the knowledge of SM and Higgs** to strengthen the basis for further exploration
  - **Explore a new phase space for new physics search** and **extension of flavour measurements**
- **Totally new machine and challenges for detectors and physics**
  - Can redo LEP program in few minutes (and with much better detectors)
- **Up to four detectors to exploit the vaste physics program**
  - Possibility to focus on different aspects (as it was done for LHC)

THE UNIQUENESS OF FCC-ee

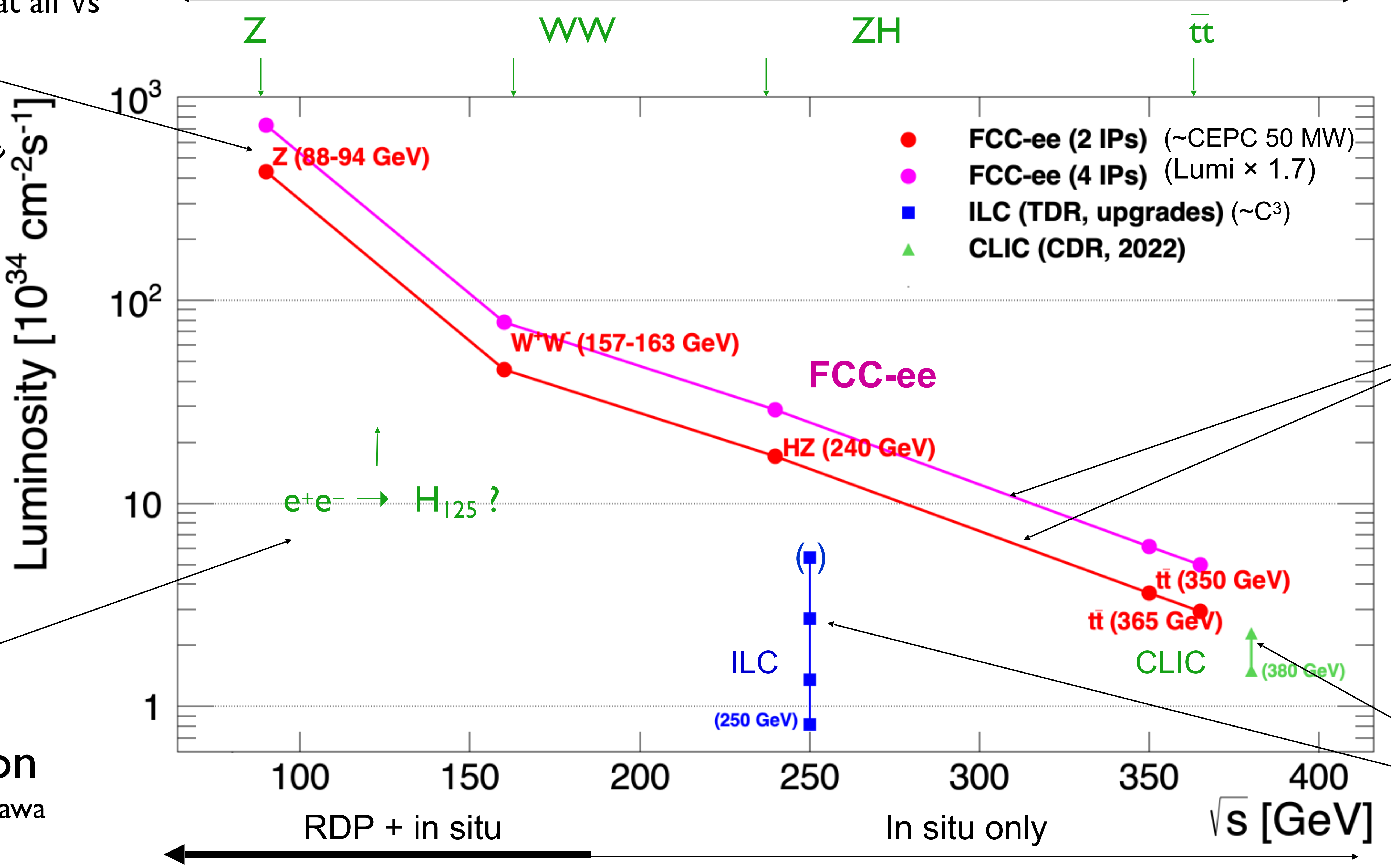
With respect to linear collider's 1st stage

Optimal energy range for SM particles

Sharpen and challenge our knowledge of already existing physics

LEP1 statistics in a few minutes

Detector calibration/alignment at all √s



Highest luminosities

Less running time for a given physics outcome

Better physics outcome for a given running time

Increase discovery potential

Serve up to 4 interaction points

Net overall gain in MW/ab⁻¹ or CO2-eq/ab⁻¹

Essential redundancy for precision measurements

May satisfy all detector requirements

Increase discovery potential

Enhance the community (FCC/CERN clients)

√s Monochromatisation

Unique opportunity for electron Yukawa

Motivates the competition

Luminosity is the name of the game

Precise and continuous √s, √s spread, boost determination

Both with resonant depolarisation (RDP) and with collision events in up to four detectors

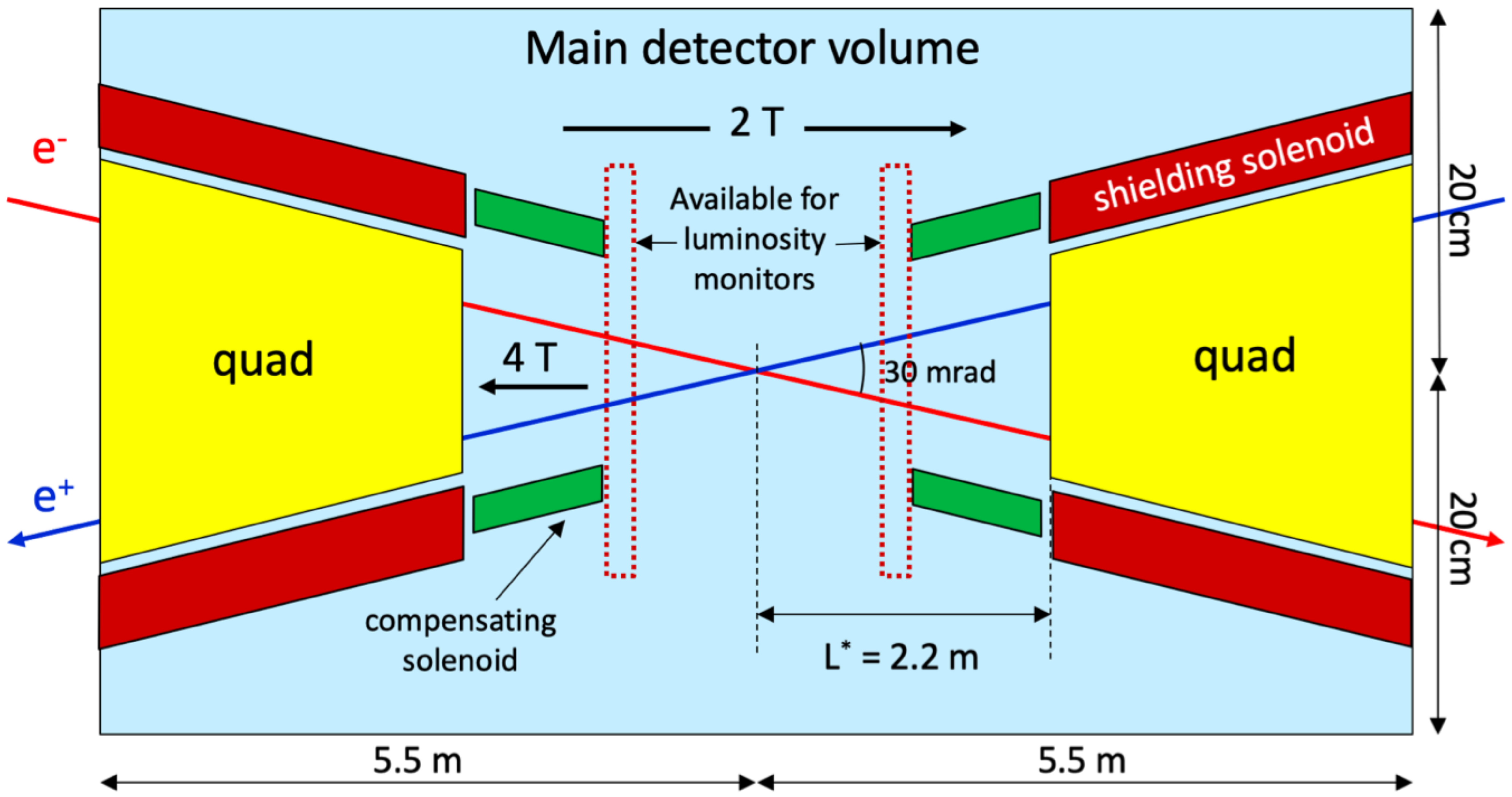
Essential for precision measurements

Slide from P. Janot

EXPERIMENTAL CHALLENGES

See talk by M. Boscolo

- **30 mrad beam crossing angle**
  - Detector B-field limited to 2 Tesla at Z-peak operations
  - Tightly packed MDI region
- **Bunch spacing down to 20ns**
  - Or less with 4IPs
  - Power management and cooling (no power pulsing)
- **Extremely high luminosities**
  - High statistical precision – control of systematics down to 10^{-6} level
  - Online/offline handling of $O(10^{13})$ events for precision physics



- **Physics events at up to 100 kHz**
  - Detector response ≲ 1 μs (and faster!) to minimise dead-time and event overlaps (pile-up)
  - Strong requirements on sub-detector front-end electronics and DAQ systems keeping low material budget

PHYSICS & DETECTOR REQUIREMENTS HIGGS/EW/TOP

M. Dam

"Higgs Factory" Programme

- At two energies, 240 and 365 GeV, collect in total
  - 1.2M HZ events and 75k WW → H events
- Higgs couplings to fermions and bosons
- Higgs self-coupling (2-4 σ) via loop diagrams
- Unique possibility: measure electron coupling in s-channel production $e^+e^- \to H$ @ $\sqrt{s}$ = 125 GeV

DETECTOR REQUIREMENTS

- Momentum resolution at $p_T \sim 50$ GeV of $\sigma_{p_T}/p_T \simeq 10^{-3}$ commensurate with beam energy spread
- Jet energy resolution of $30\%/\sqrt{E}$ in multi-jet environment for Z/W separation
- Superior impact parameter resolution for c, b tagging

Ultra Precise EW Programme & QCD

Measurement of EW parameters with factor ~300 improvement in *statistical* precision wrt current WA

- 5×10^{12} Z and 10^8 WW
  - m_Z, Γ_Z, Γ_{inv}, $\sin^2\theta_W^{eff}$, R^Z_ℓ, R_b, α_s, m_W, Γ_W,…
- 10^6 tt
  - m_{top}, Γ_{top}, EW couplings

Indirect sensitivity to new phys. up to Λ=70 TeV scale

DETECTOR REQUIREMENTS

- Absolute normalisation (luminosity) to 10^{-4}
- Relative normalisation (e.g. Γ_{had}/Γ_ℓ) to 10^{-5}
- Momentum resolution "as good as we can get it"
  - Multiple scattering limited
- Track angular resolution < 0.1 mrad (BES from μμ)
- Stability of B-field to 10^{-6} : stability of $\sqrt{s}$ meast.

…are these requirements enough to design our best detector?

FCC-ee AT THE INTENSITY FRONTIER

➤ **TeraZ offers additional pillars to the FCC-ee Higgs/EW/Top physics programme:**

- ➤ **Flavour:** Enormous statistics 10^{12} bb, cc, Clean environment, favourable kinematics (boost), extend/complement reach of Belle2 and LHCb
- ➤ **Tau:** Enormous statistics: 1.7 10^{11} $\tau\tau$ events. Much improved measurements of mass, lifetime, BR's
- ➤ **BSM/Feebly coupled Particles:** directly observe new feebly interacting particles below m_Z. Difficult signatures, including LLP's, but also Axion-like particles, Dark photons, Heavy Neutral Leptons and ultra-rare Z (and W) decays,

Flavour physics programme

- Formidable vertexing ability; b, c, s tagging
- Superb electromagnetic energy resolution
- Hadron identification covering the momentum range expected at the Z

Tau physics programme

- Momentum resolution
  - Mass measurement, LFV search
- Precise knowledge of vertex detector dimensions
  - Lifetime measurement
- Tracker and ECAL granularity and e/μ/π separation
  - BR measurements, EWPOs, spectral functions

Rare/BSM processes, e.g. Feebly Coupled Particles

- Sensitivity to far-detached vertices
- Tracking: more layers, continuous tracking
- Calorimetry: granularity, tracking capability
- Extended detector volume
- Full acceptance ⇒ Detector hermeticity

More case studies will lead to more detector requirements

FCC

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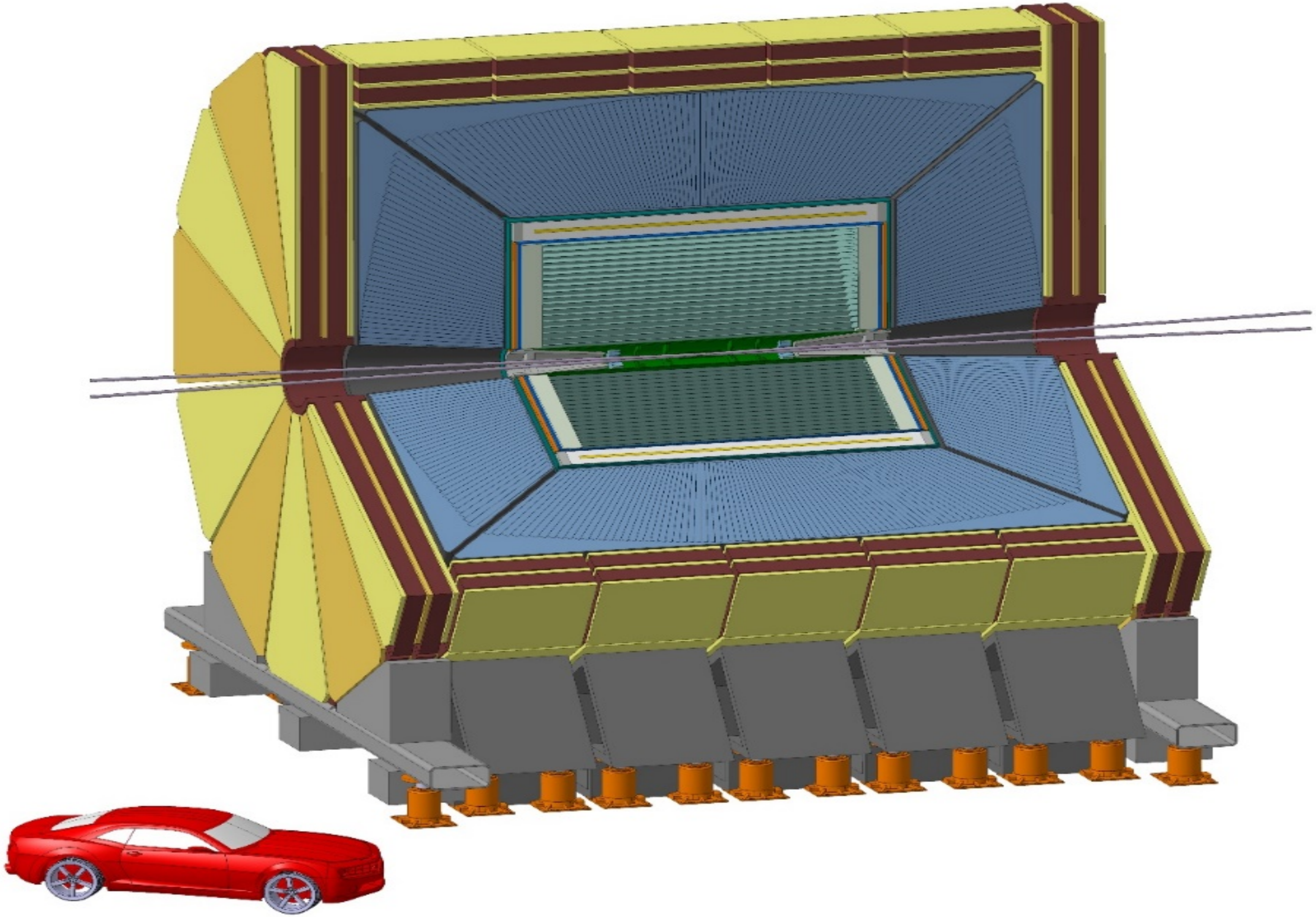
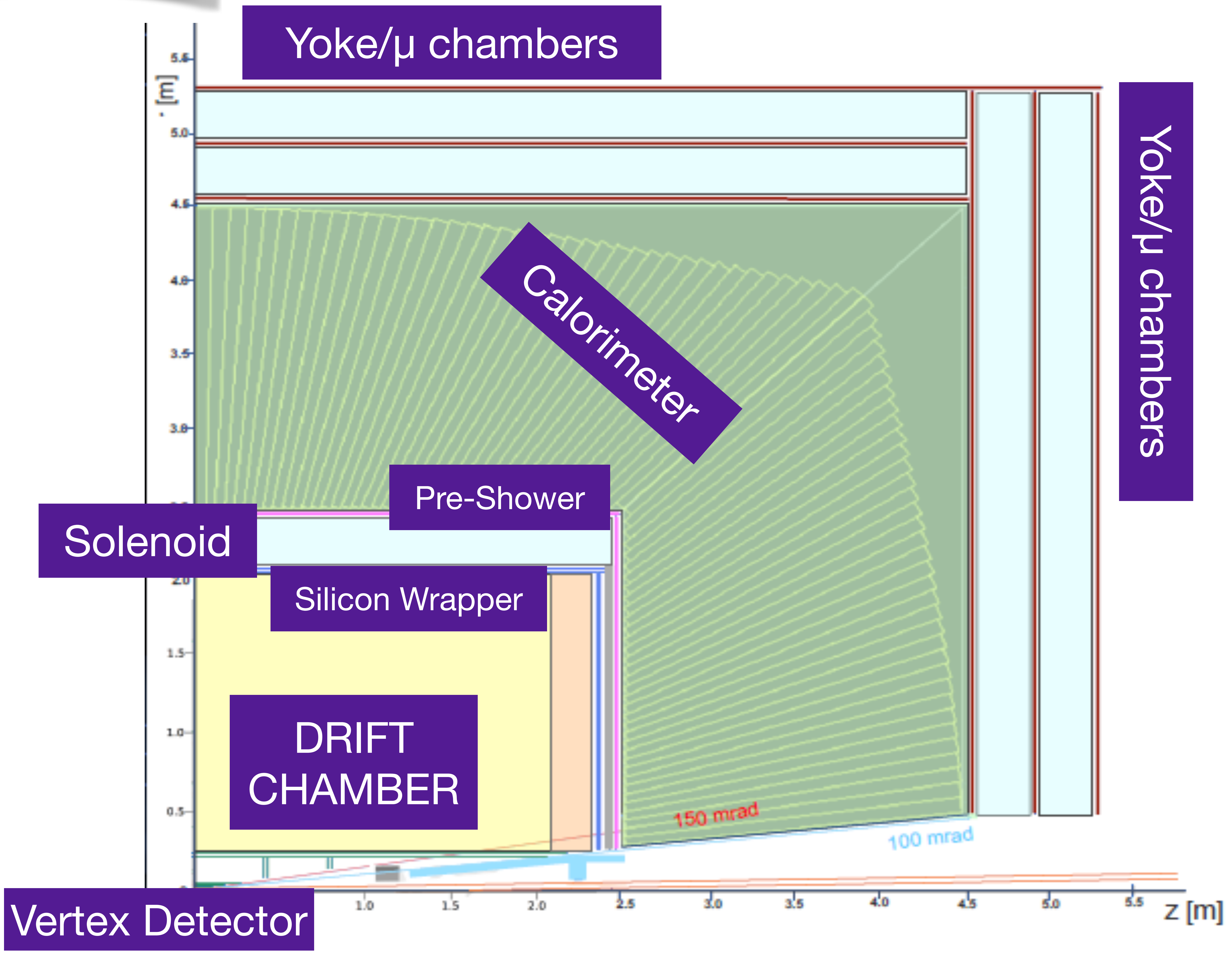
If all these constraints are met, Higgs and top programme probably OK (tbc)

IDEA (Innovative Detector for e^+e^- Accelerator)



FCC

IDEA CONCEPT DETAILS



Small magnet

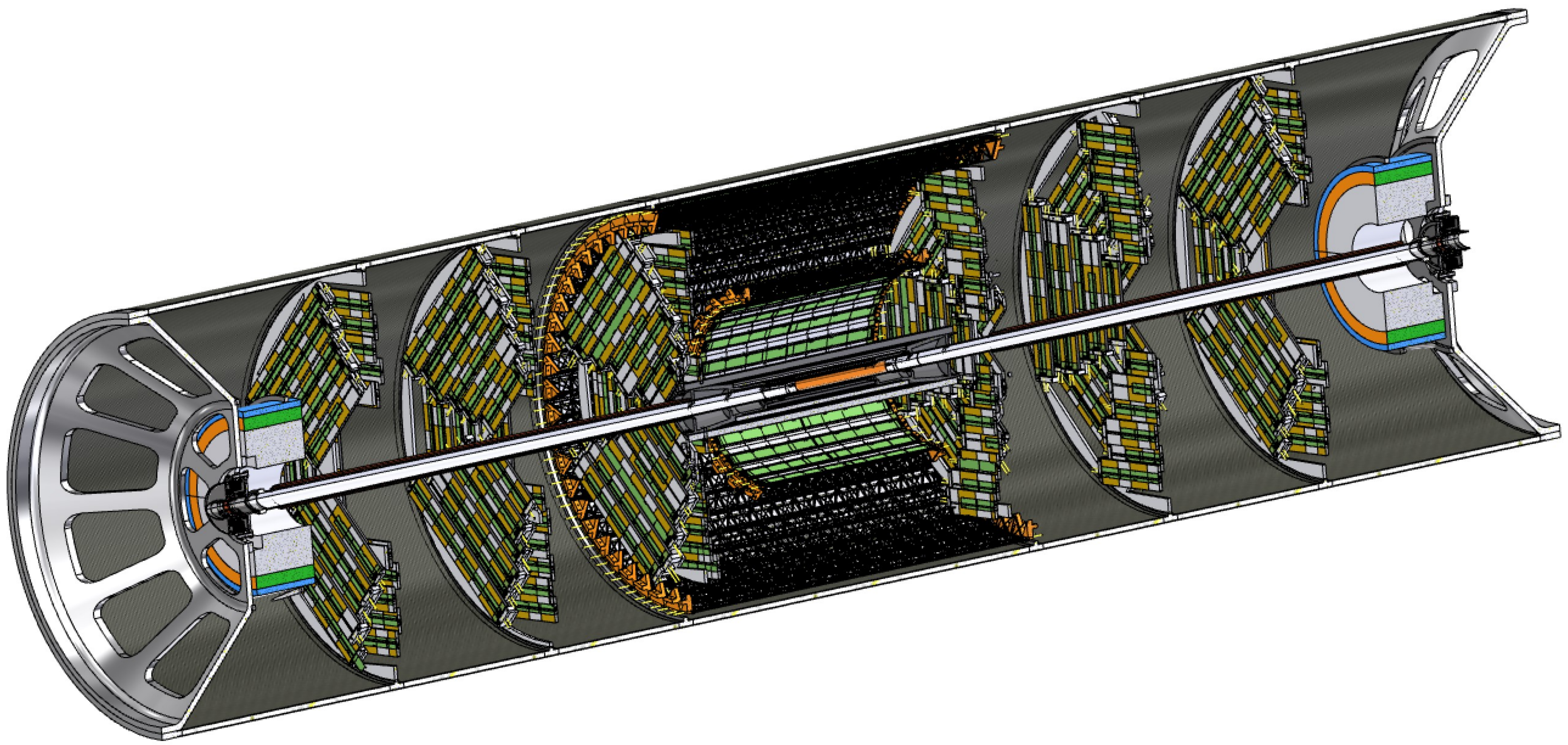
↓

Small yoke

- Tracking → 150 mrad
  - *No material in front of luminometer*
- Calorimetry → 100 mrad

See talk by N. De Filippis, F. Palla

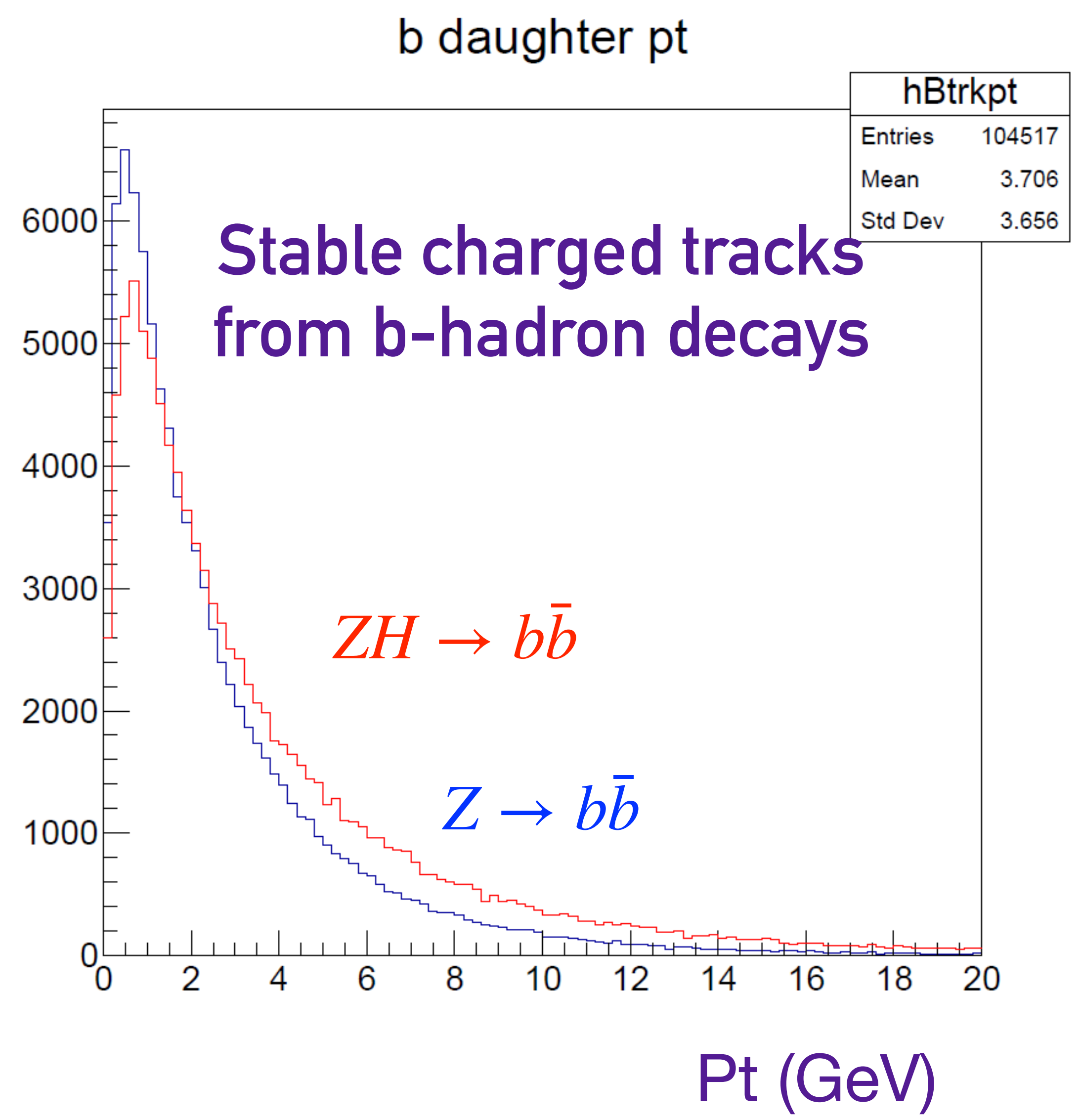
VERTEX DETECTOR

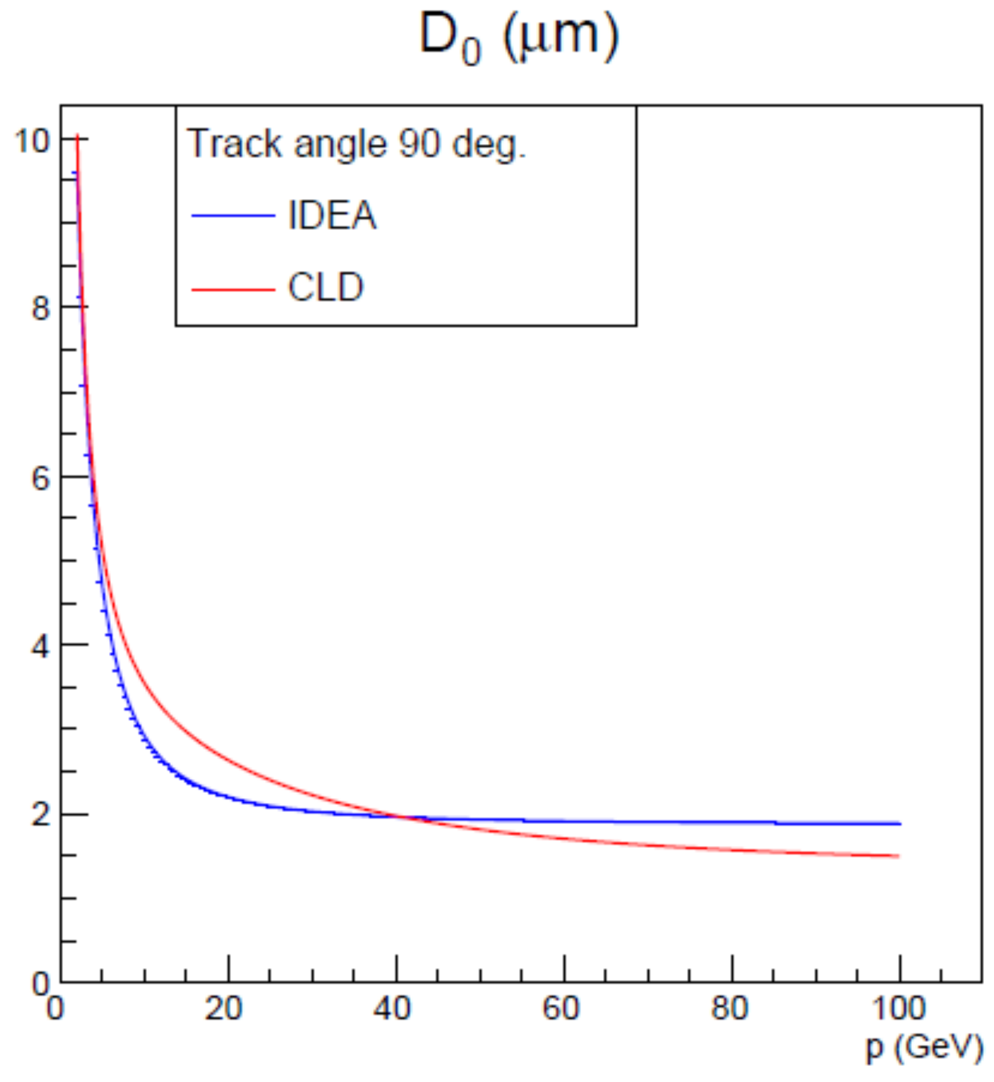


Vertex detector (ARCADIA DMAPS)
* Modules of $25 \times 25\ \mu m^2$ pixel size
* 3 barrel layers at: 13.7, 22.7 and 33 mm radius

Outer tracker:
Modules of $50 \times 150\ \mu m^2$ pixel size (ATLASPIX3)
- **Intermediate barrel layer at 13 cm radius**
  (improved reconstruction for $p_T > 40$ MeV tracks)
- **Outer barrel at 31.5 cm radius**
- 3 disks per side

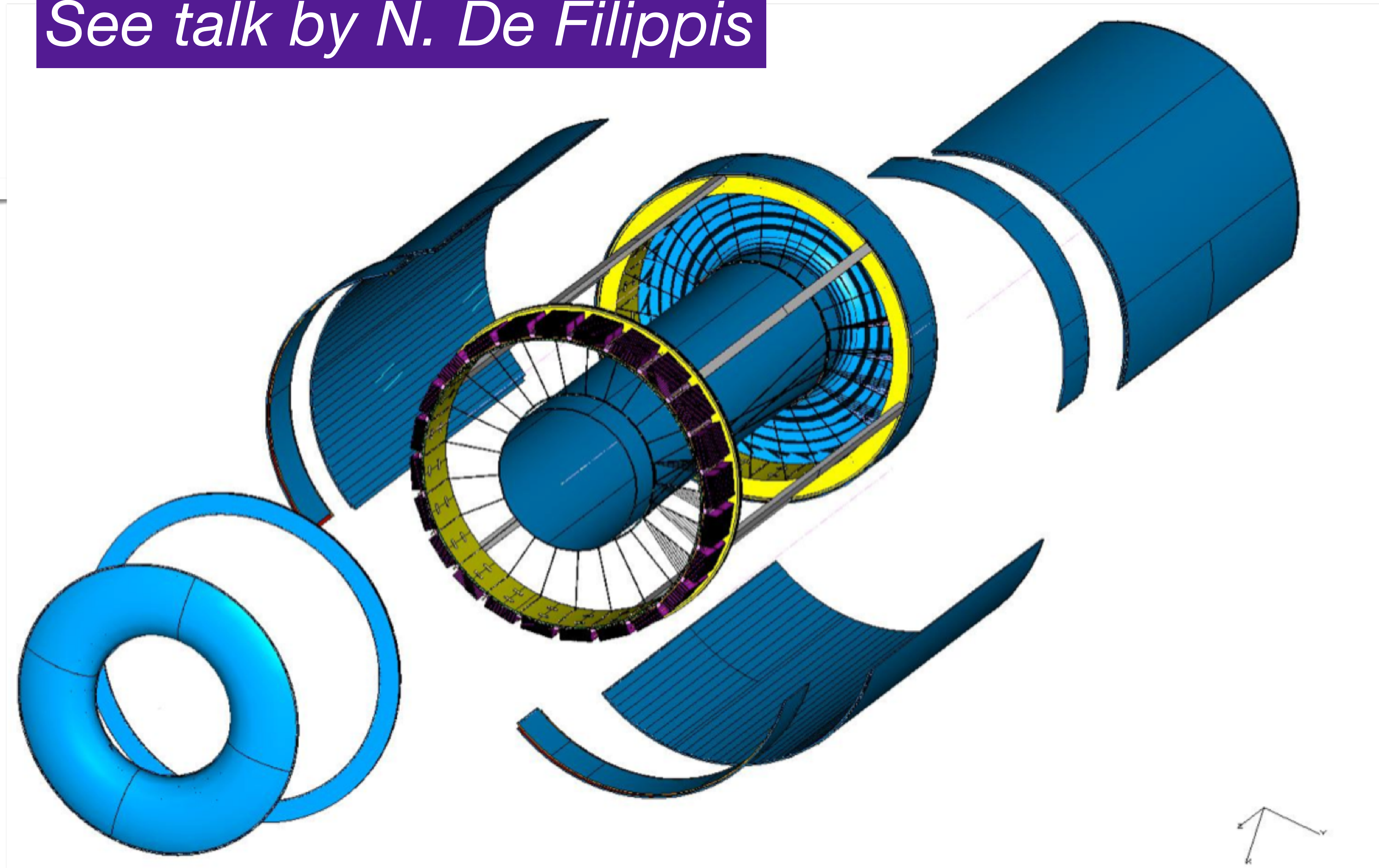
- **Based on MAPS technology, using the ARCADIA R&D program**
  - **new layout being developed, more realistic wrt the CDR version**
  - Profiting of the small beam pipe D~2cm, covering $cos\theta < 0.99$
  - Very light: Total thickness per layer ~0.25% X_0
- **Simulation and Performance of the new layout in progress, but won't be much different from baseline:**
  - Point resolution ~$3\mu m$
  - ~100% efficiency and very low fake rate





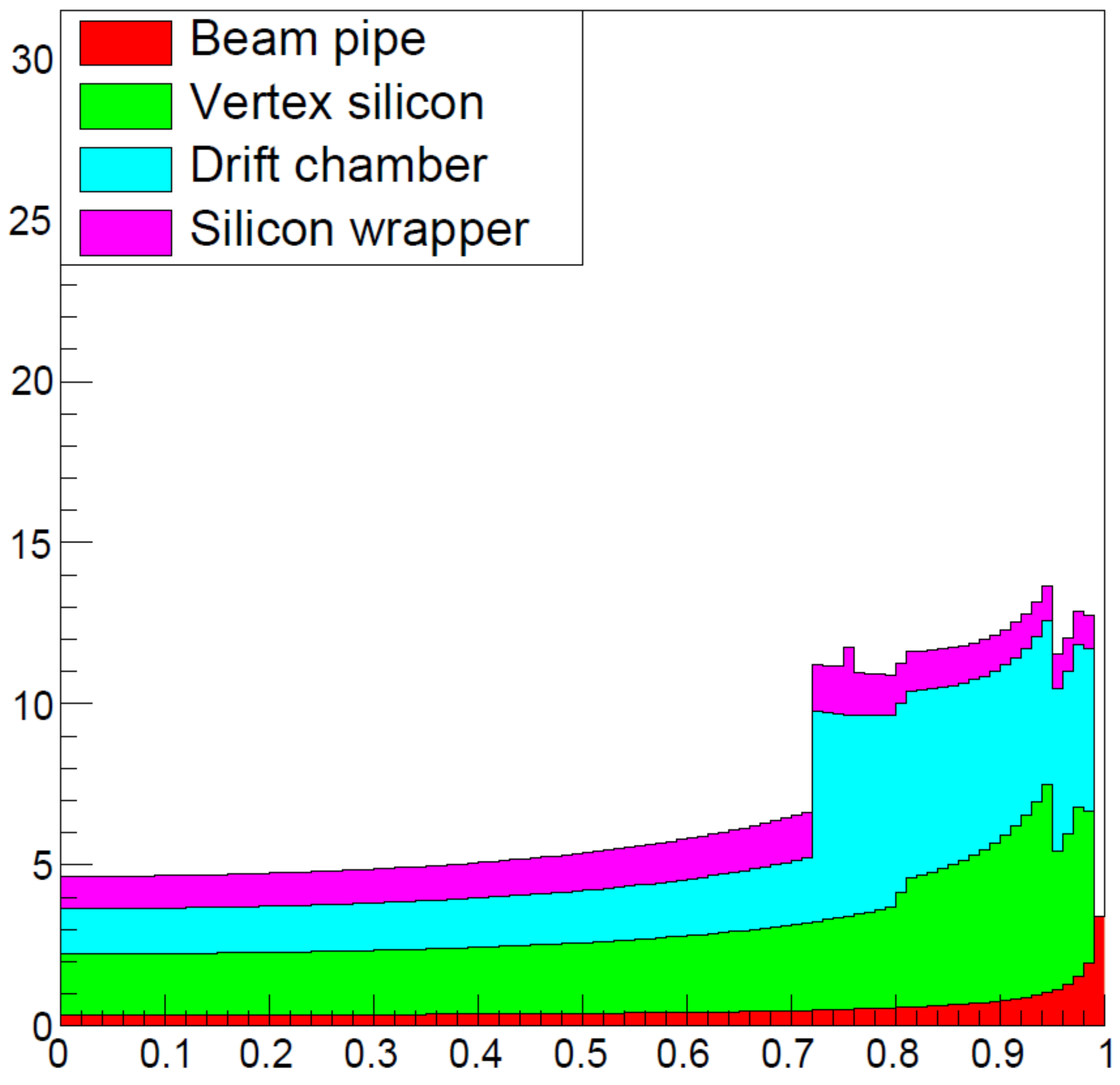
See talk by N. De Filippis

DRIFT CHAMBER



- **Extremely transparent Drift Chamber**
  - Gas: 90% He – 10% iC_4H_{10}
  - Radius 0.35 – 2.00 m
  - Total thickness: 1.6% of X_0 at 90°
    - **Tungsten wires dominant contribution**
  - 112 layers for each 15° azimuthal sector
  - max drift time: 350 ns

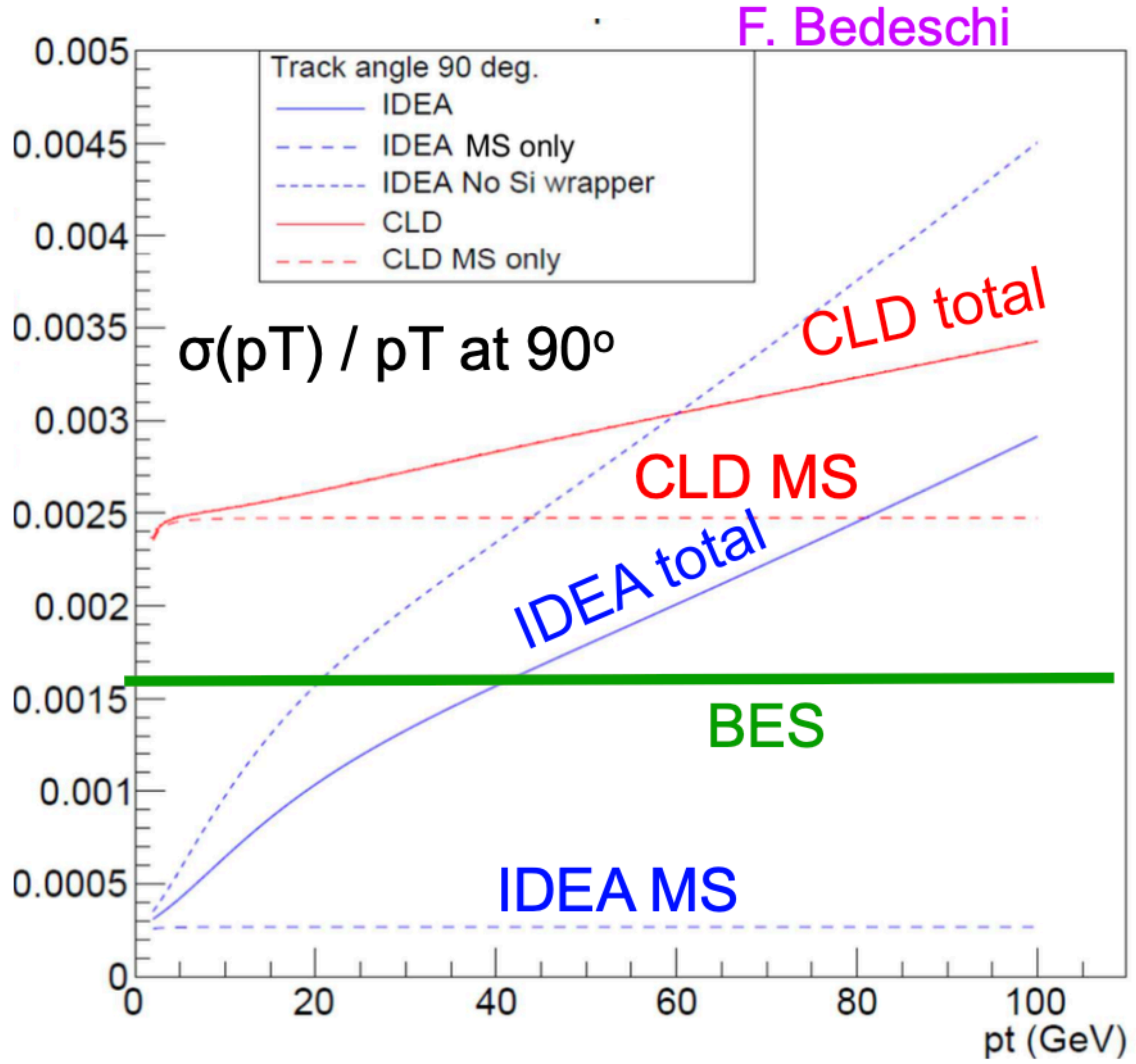
IDEA: Material vs. cos(θ)



BES inherent to the machine.
~ 0.16% at 240 GeV
(~ 0.13% at the Z)

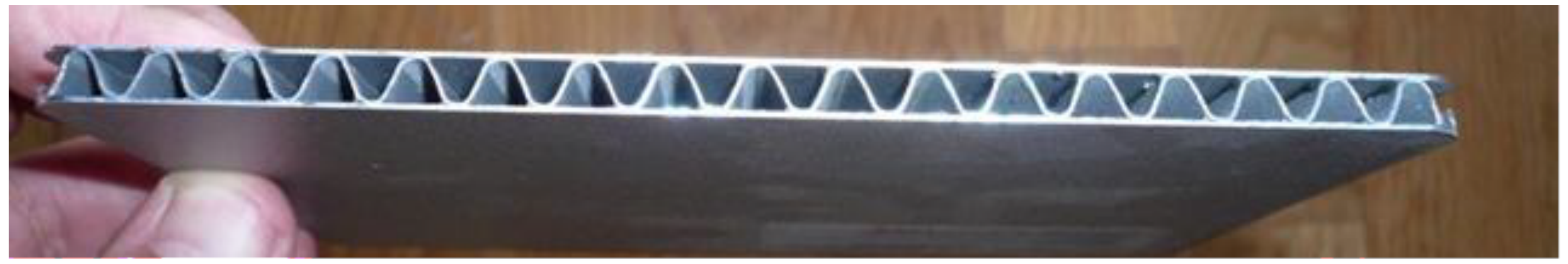
Ideally: σ(p) / p ≈ rel. BES

- **Z or H decay muons in ZH events have rather small p_T**
  - Transparency more relevant than asymptotic resolution



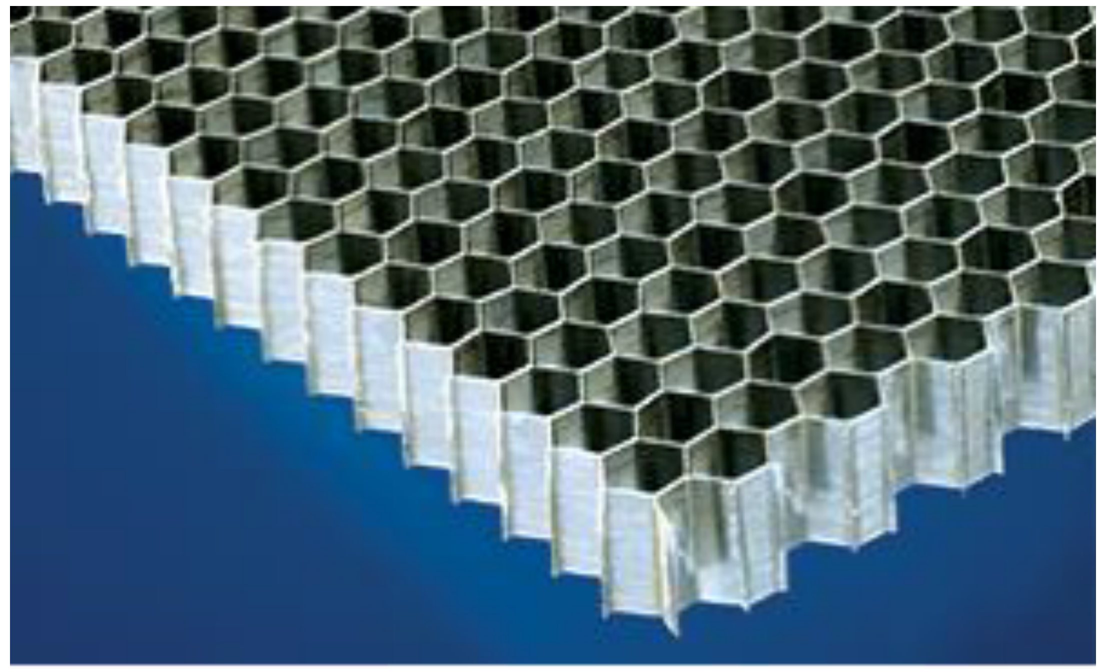
patrizia azzi - BNL April 25th 2023

SILICON WRAPPER & MAGNET

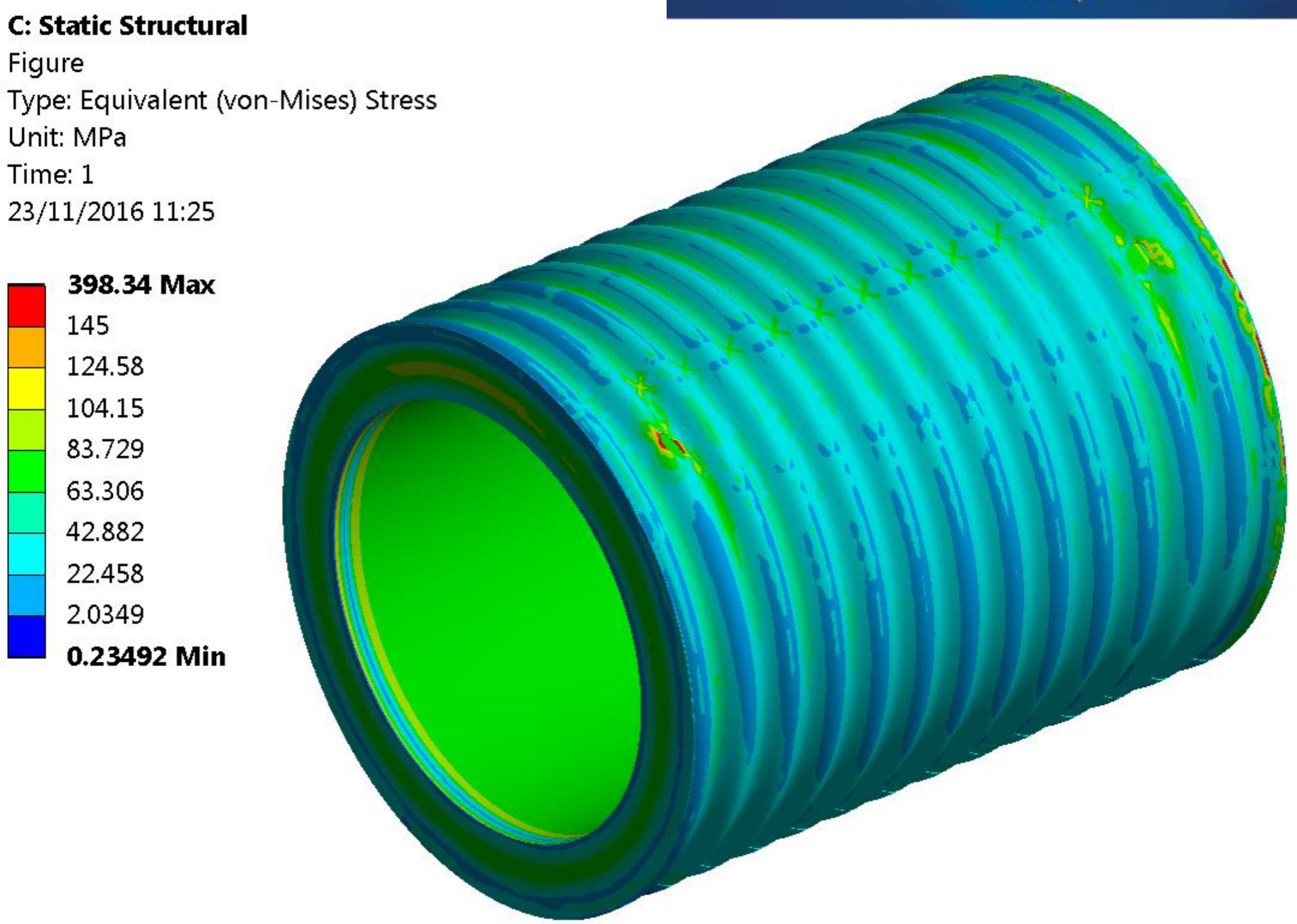


- **Silicon Wrapper between Drift Chamber and Solenoid**
  - Provides 3D information at the exit point of the Drift Chamber (improves momentum resolution)
  - Silicon with timing capabilities can help the PID (such as π/K separation around 1GeV and above)
  - ATLASPix3 baseline, LGAD technology an option under study

Courtesy of H. TenKate

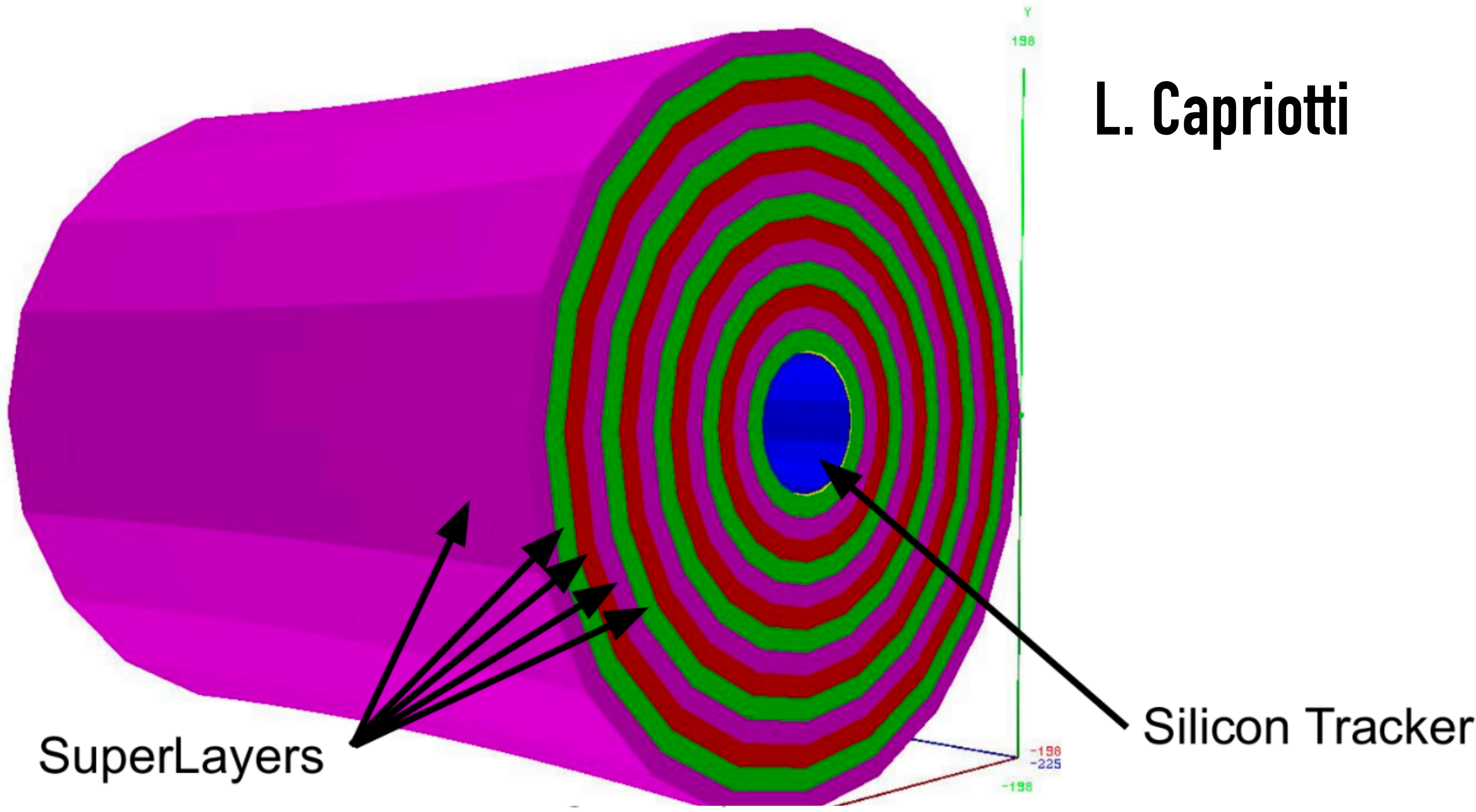


- **Ultra light 2T solenoid:**
  - Radial envelope 30 cm
  - Single layer self-supporting winding (20 kA)
    - **Cold mass: X_0 = 0.46, λ = 0.09**
  - Vacuum vessel (25 mm Al): X_0 = 0.28
    - **Can improve with new technology**
      - Corrugated plate: X_0 = 0.11
      - Honeycomb: X_0 = 0.04



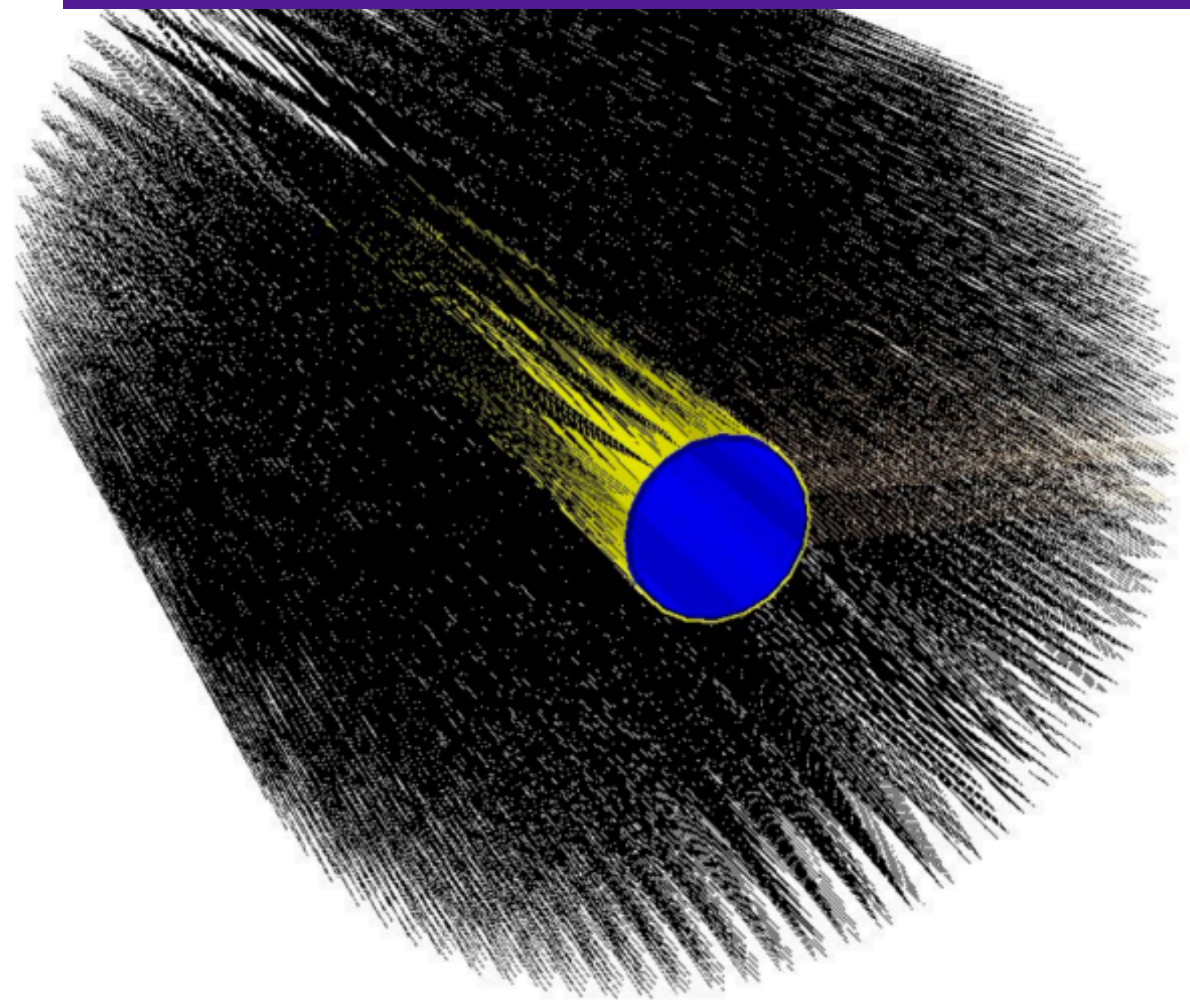
TRACKING SYSTEM SIMULATION & PERFORMANCE

See talk by M. Selvaggi on Delphes



- **Delphes provides the response of a multipurpose detector in a parameterised way**
- **Addition of several ORIGINAL features and tools to the official Delphes code:**
  - **Full covariance matrix description for tracks**: possibility to study in detail detector configurations (position of Silicon layers) even in FastSim
  - **Vertexing:** for primary and secondary vertexing with external constraint and track addition/removal feature. Also treatment of Long lived particles.
  - **ClusterCounting:** returns the cluster info given a volume crossed (stand-alone), returns a track complete with cluster information in Delphes output
  - **Tuning of electron resolution**: study of resolution of electron tracks in IDEA to tune the Delphes parameterization
- **Full simulation description with G4 being ported to DD4HEP geometry**
  - Full simulation of new developments/components to be implemented. Lots of possibilities to collaborate

DRIFT CHAMBER IN DD4HEP

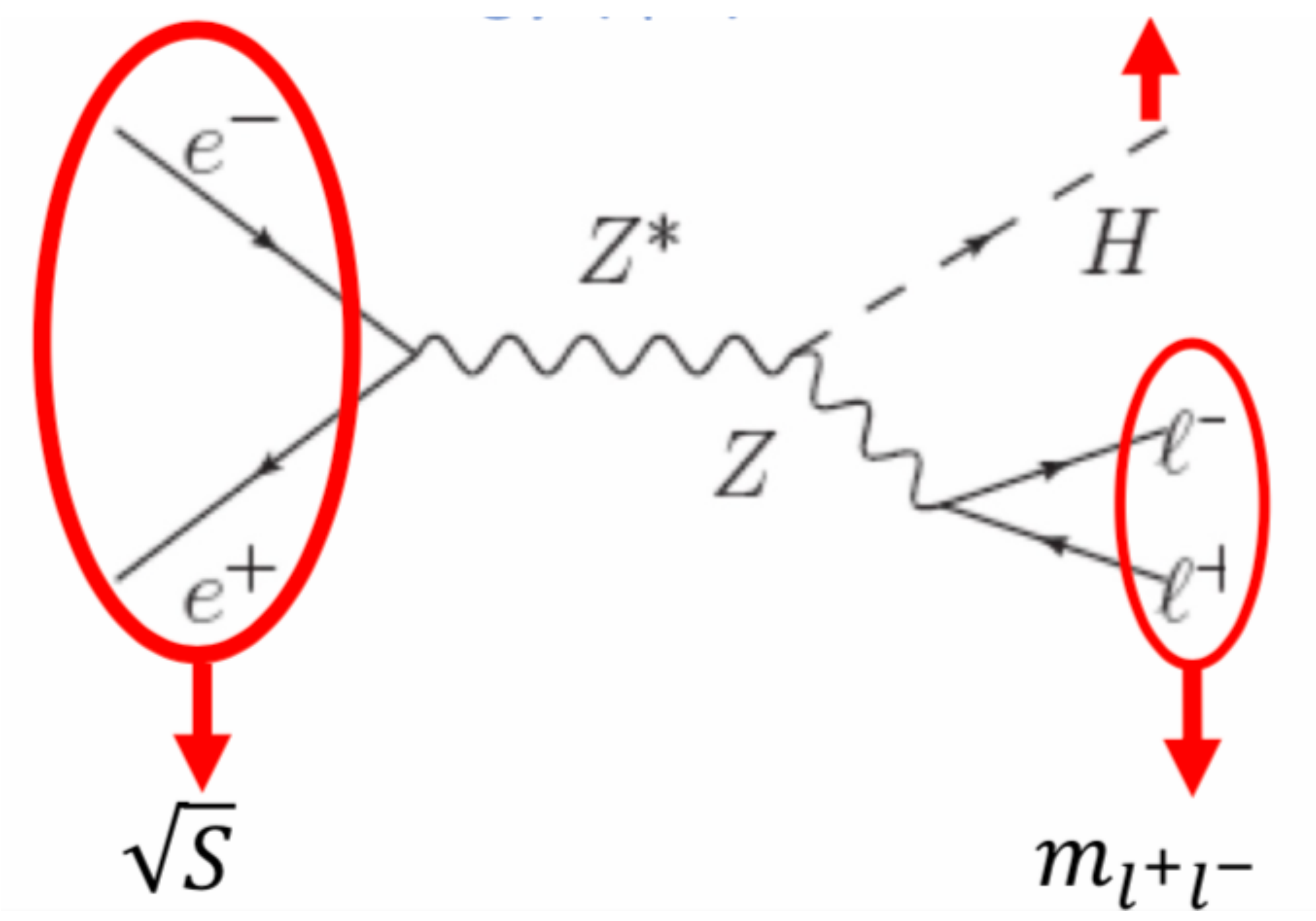


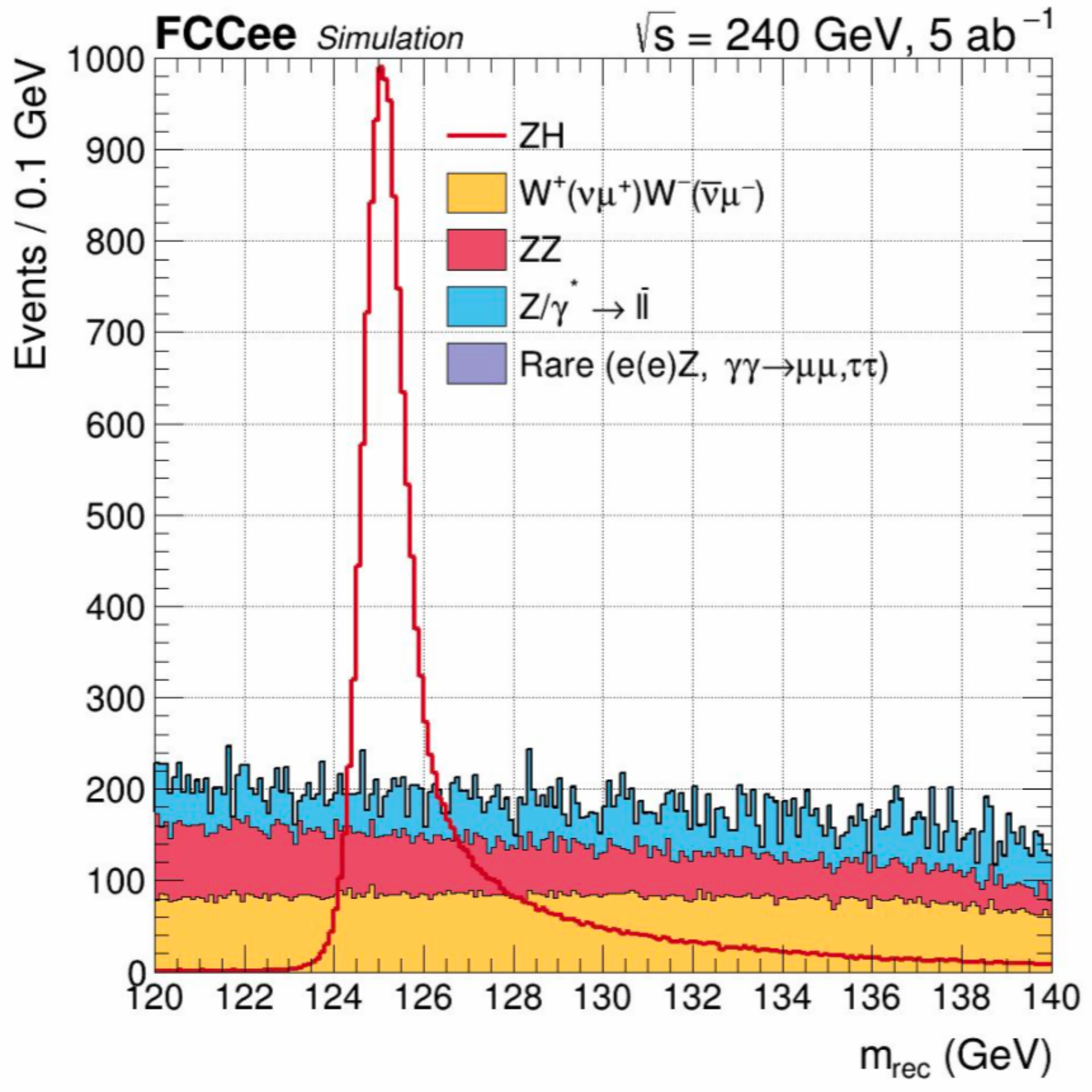
Only 2% of wires shown

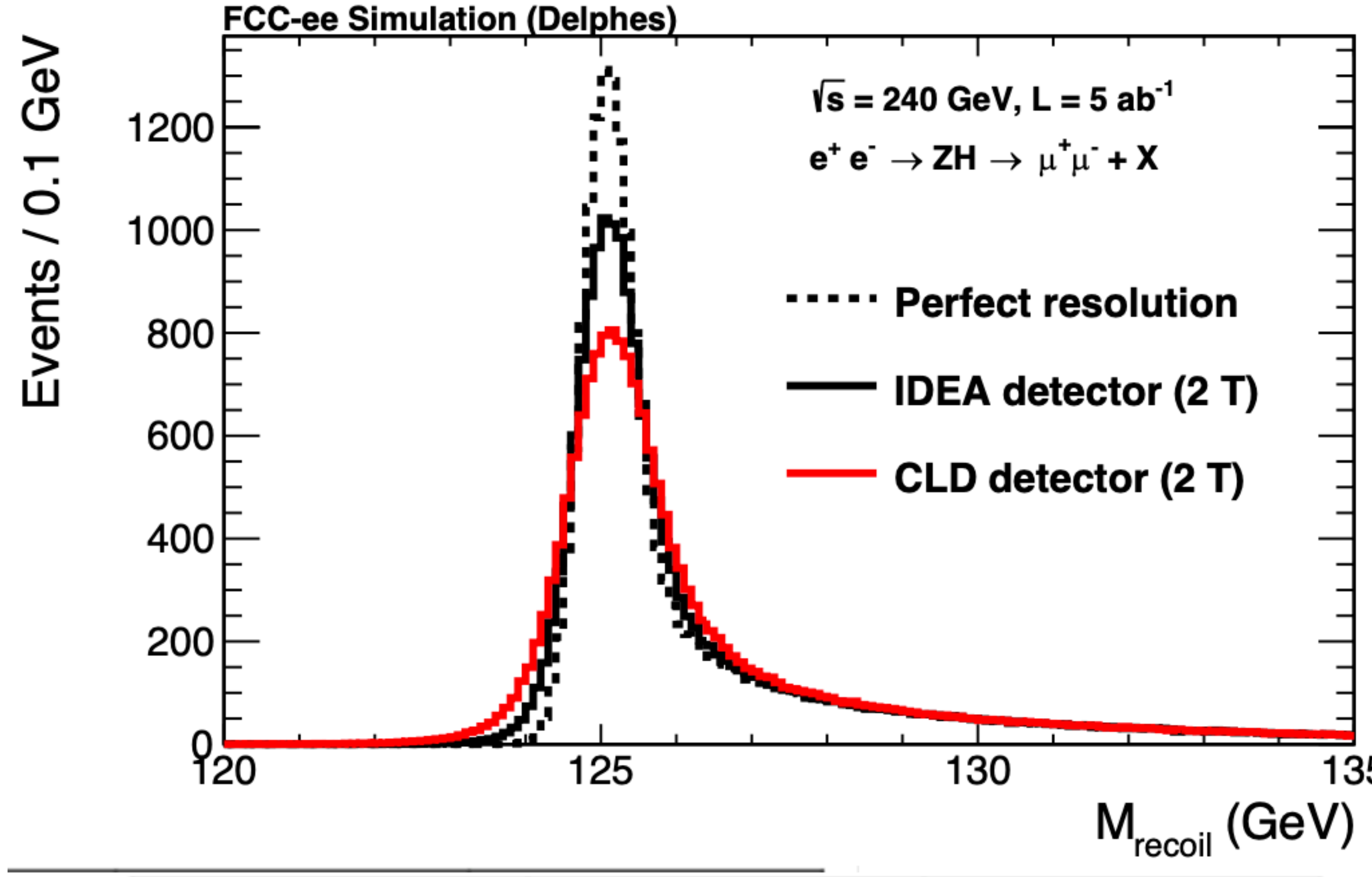
TRACKING REQUIREMENTS: HIGGS MASS AND CROSS SECTION

DELPHES BASED STUDY 2107.04509

$e^+e^- \to ZH, Z \to \mu\mu$







$$m^2_{\text{recoil}} = (\sqrt{s} - E_{l\bar{l}})^2 - p^2_{l\bar{l}} = s - 2E_{l\bar{l}}\sqrt{s} + m^2_{l\bar{l}}$$

Recoil mass affected by :

- The beam energy spread
- The momentum resolution (and the ISRs for the tail)

Higgs mass measurement:

$\Delta(m_H) < O(\Gamma_H)$ i.e. 4 MeV desirable in view of $e^+e^- \to H$

Main TK	Δm_H (MeV)	$\Delta\sigma$ (%)
IDEA 2T	**6.70**	**1.07**
CLD 2T	**9.01**	**1.12**
IDEA 3T	**5.78**	**1.06**
Perfect resol	**4.75**	**1.04**

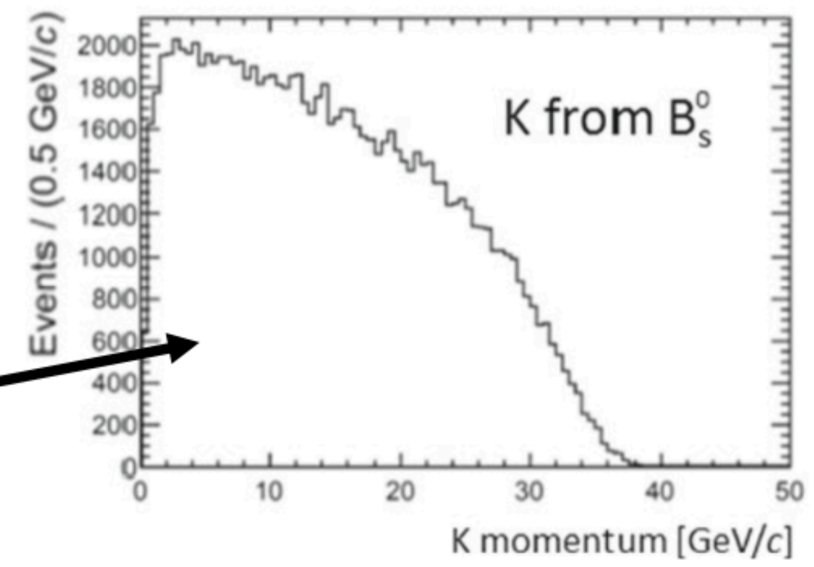
PARTICLE IDENTIFICATION CAPABILITIES (PID)

- **Essential for flavour physics / spectroscopy**

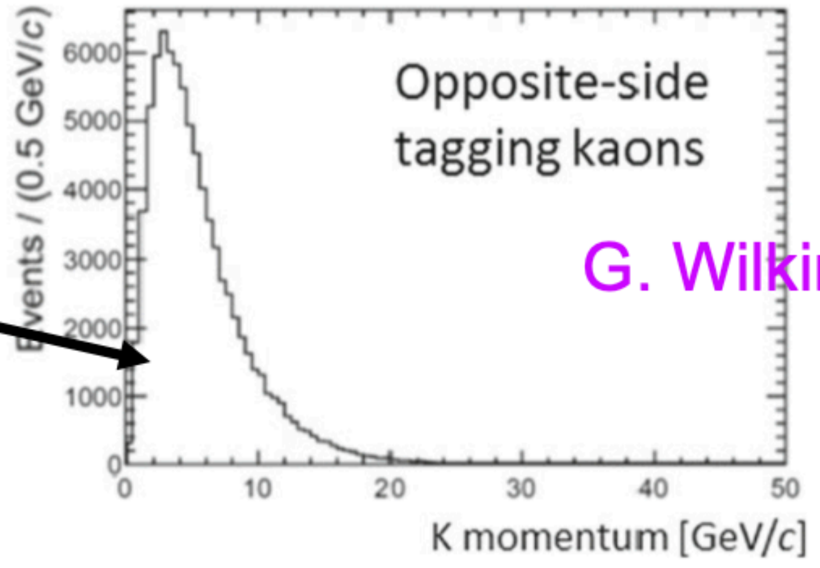
  PID needed in a large momentum range !

  - Suppress backgrounds

    e.g. $B_s \to D_s K$, p(K) extends up to 30 Gev



  - Time-dependent CP asymmetries: need to tag the flavour (B or Bbar) of the meson at production.
    - Use charge of 'opposite-side' Kaon ($b \to c \to s$) : p(K) very soft

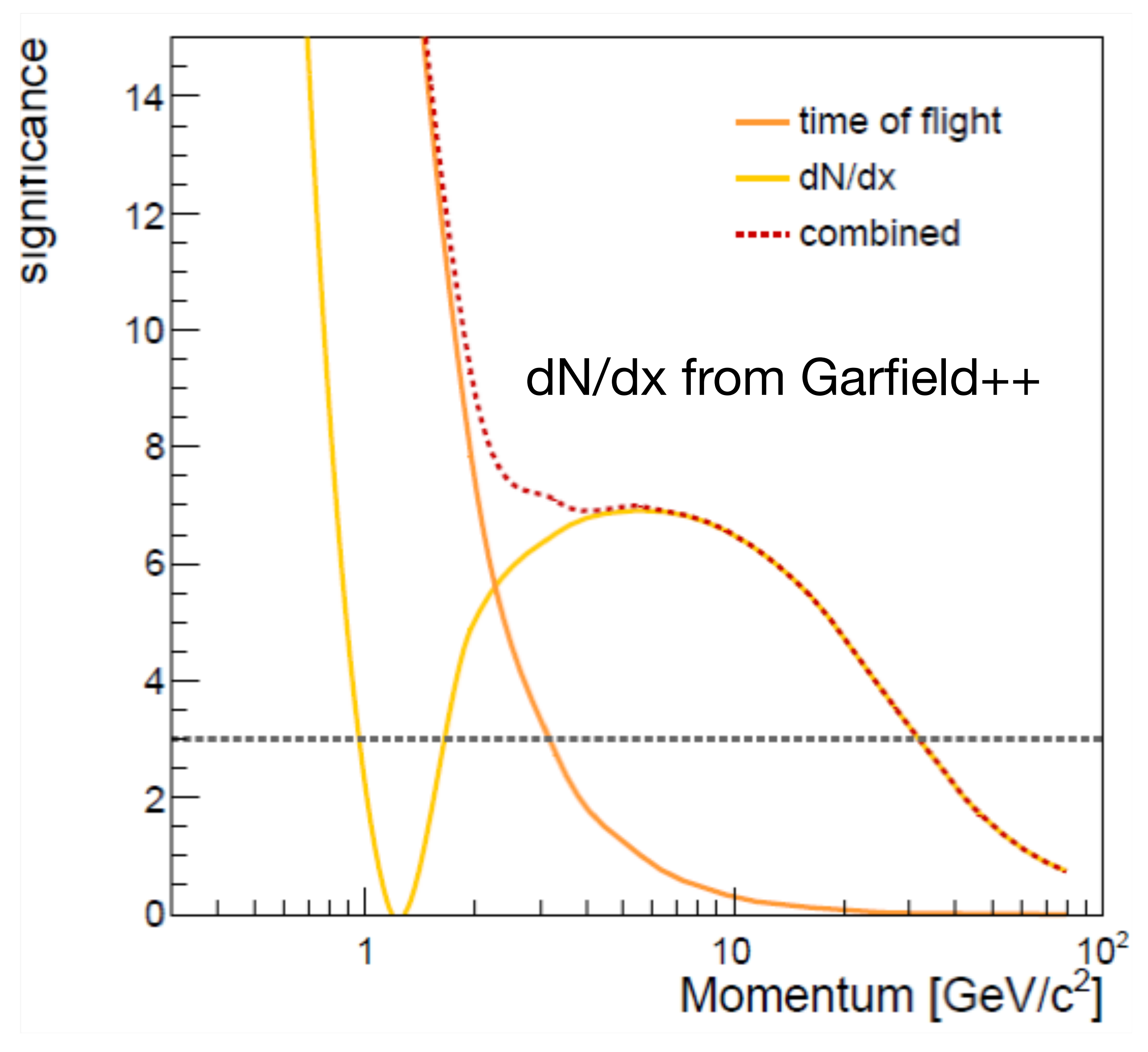


G. Wilkinson

  Typically exploit ionisation energy loss and time-of-flight. Space constraints for a RICH, but ideas / work ongoing.

- **Very useful for tau physics**
  - e.g. determination of B($\tau \to \nu\ \pi$), B($\tau \to$ nu K) hence V_{us} independent of lattice predictions

- **Input to jet flavour tagging (strange tagging)**



30 ps assumed resolution for timing detector

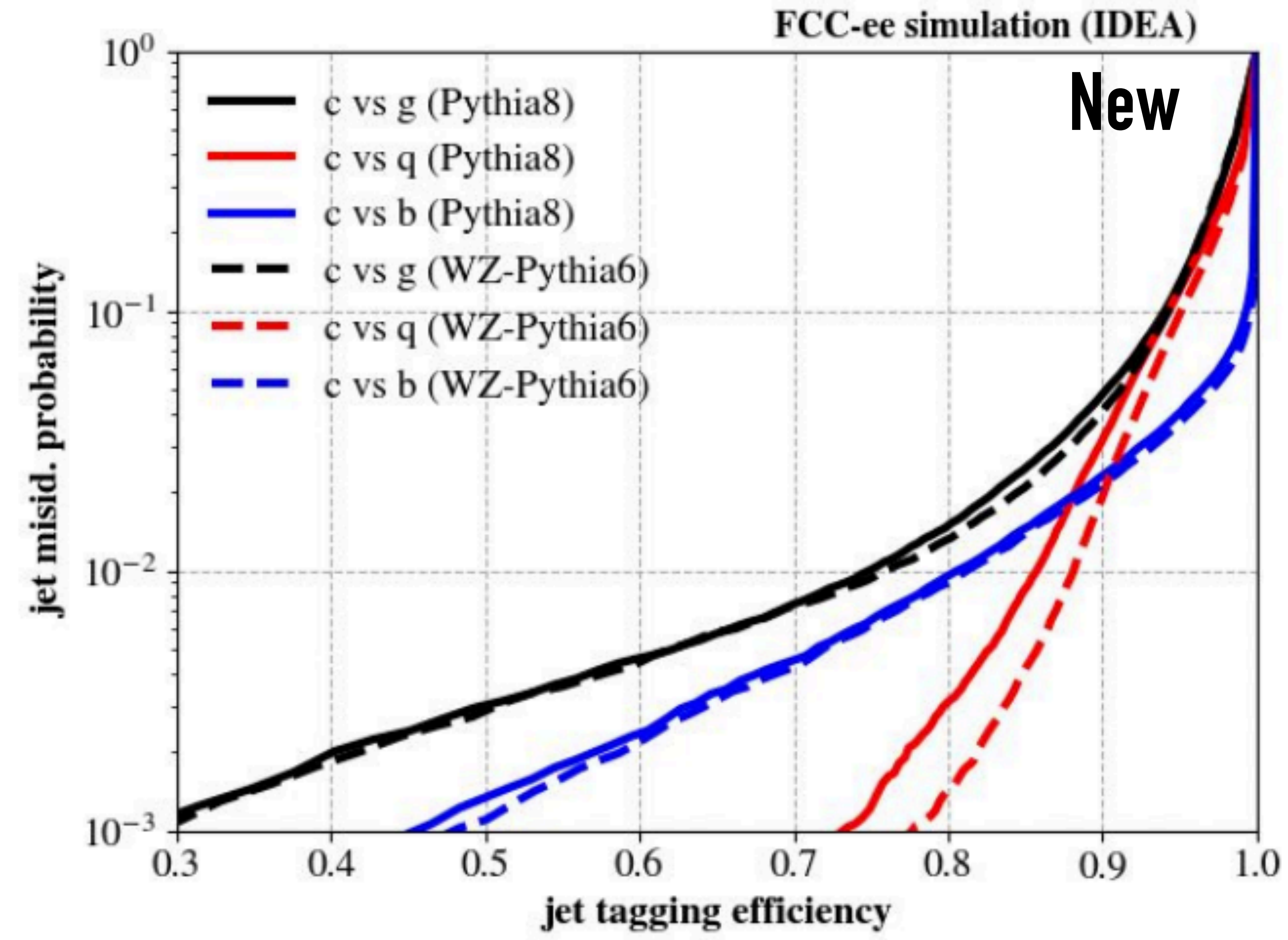
➤ **Expect > 3σ K/π separation from Cluster Counting in Drift Chamber up to ~30 GeV**

  ➤ ToF at <100 ps resolution covers the region around 1 GeV

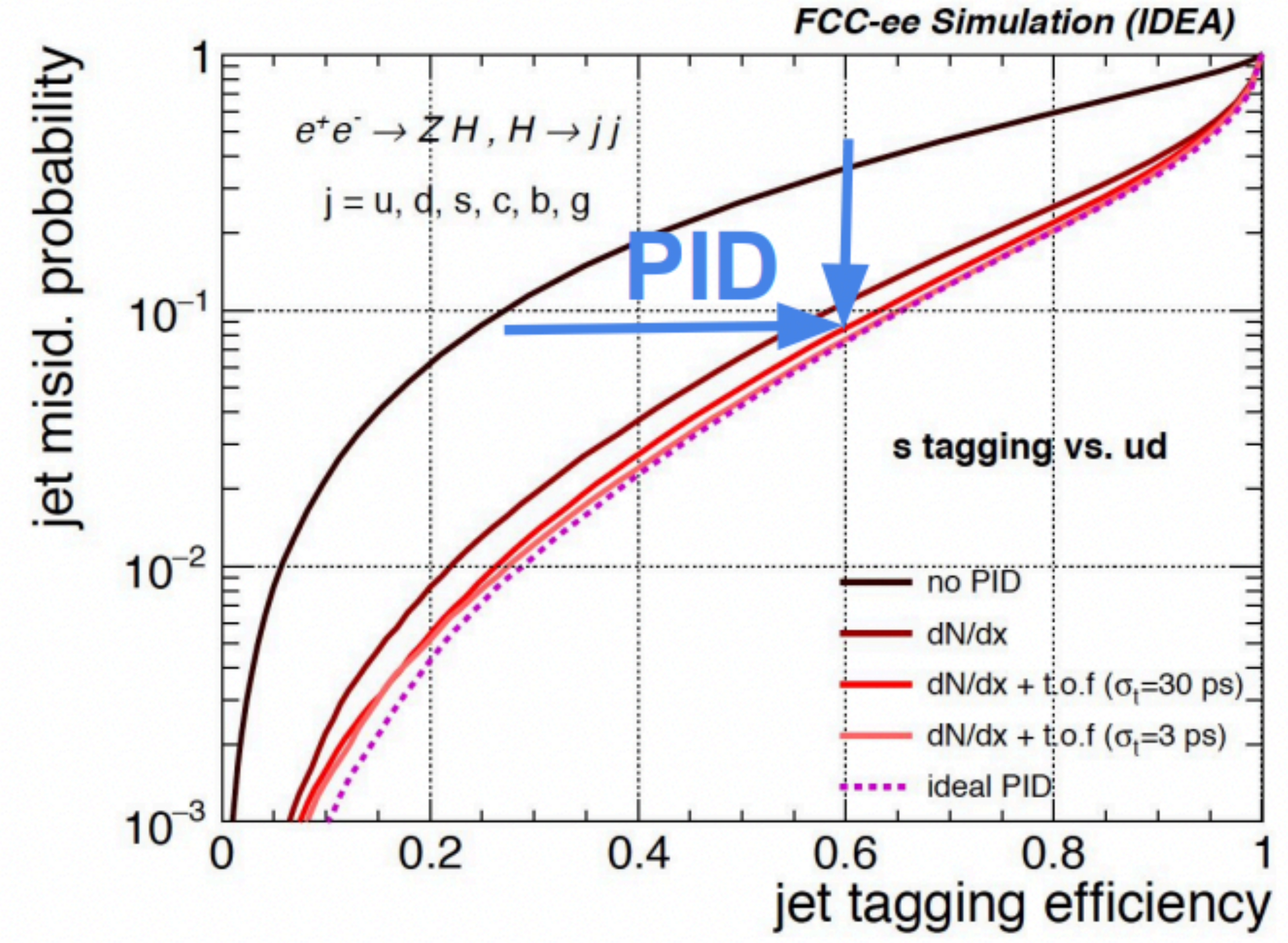
VERTEXING REQUIREMENTS (AND MORE) : HIGGS COUPLINGS TO b/c/s-QUARKS AND GLUONS

2202.03285

New document in progress for mid-term report



- **A must for any Higgs factory**
  - Precise measurement of all Higgs couplings to ff, VV
  - H(cc), H(gg) won't be measured at HL-LHC
- **Flavour tagging is the key**
  - Algorithms based on state-of-the-art advanced Neural Networks
- **Requirements on Detector:**
  - Position of innermost layer of vertex
  - Particle ID capabilities (timing?)
- **Beauty of a ML Tagger is the ability to "evolve" to include more capabilities (taus, U, D categories etc…)**



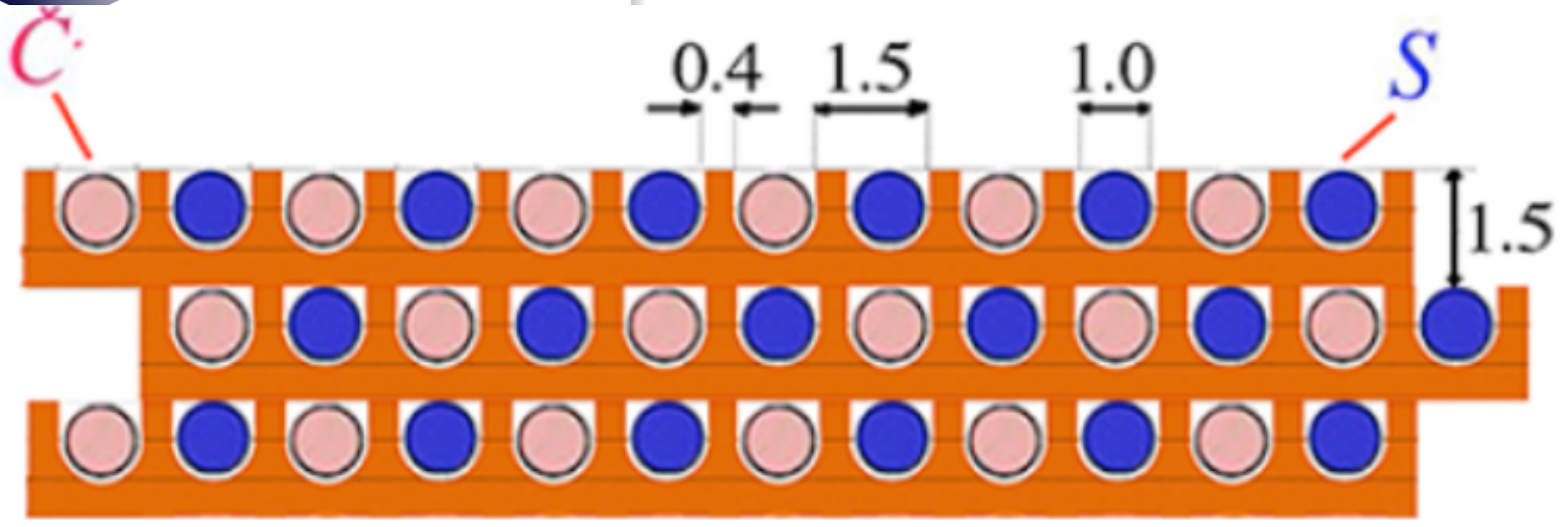
Benchmarks for flavour tags

- Final states:
  - Z(ll) H(qq) : clean, use the recoil mass agai
  - Z(vv) H(qq) : probably drives the sensitivity
  - Z(qq) H(qq) : performance depends in addition on jet pairing, see later

FCC

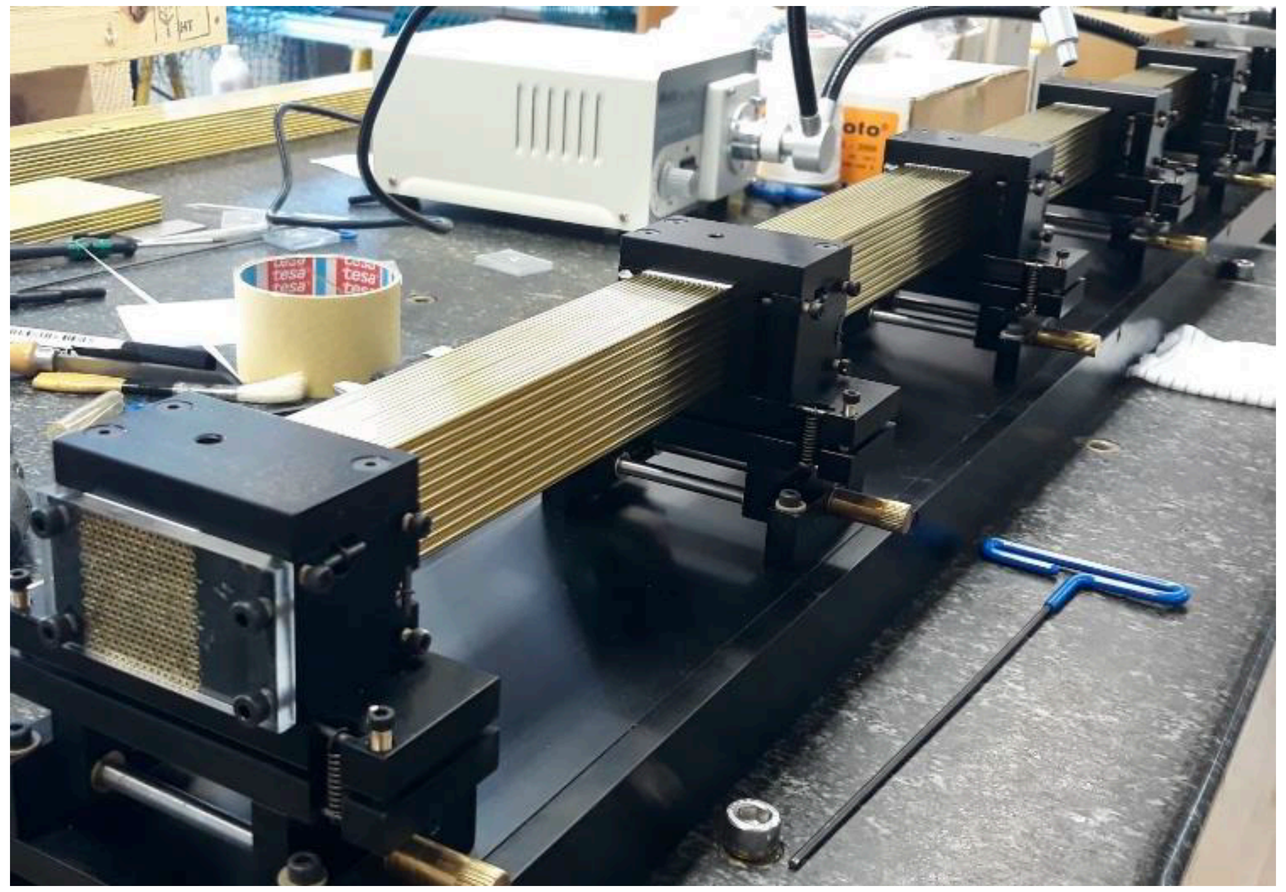
See talk by I. Vivarelli

DUAL READOUT CALORIMETRY



Alternate
Cherenkov fibers
Scintillating fibers

~2m long capillaries



- **Measure simultaneously:**
  - Scintillation signal (S)
  - Cherenkov signal (Q)
- **Calibrate both signals with electrons**
- **Unfold event by event f_{em} to obtain corrected energy**

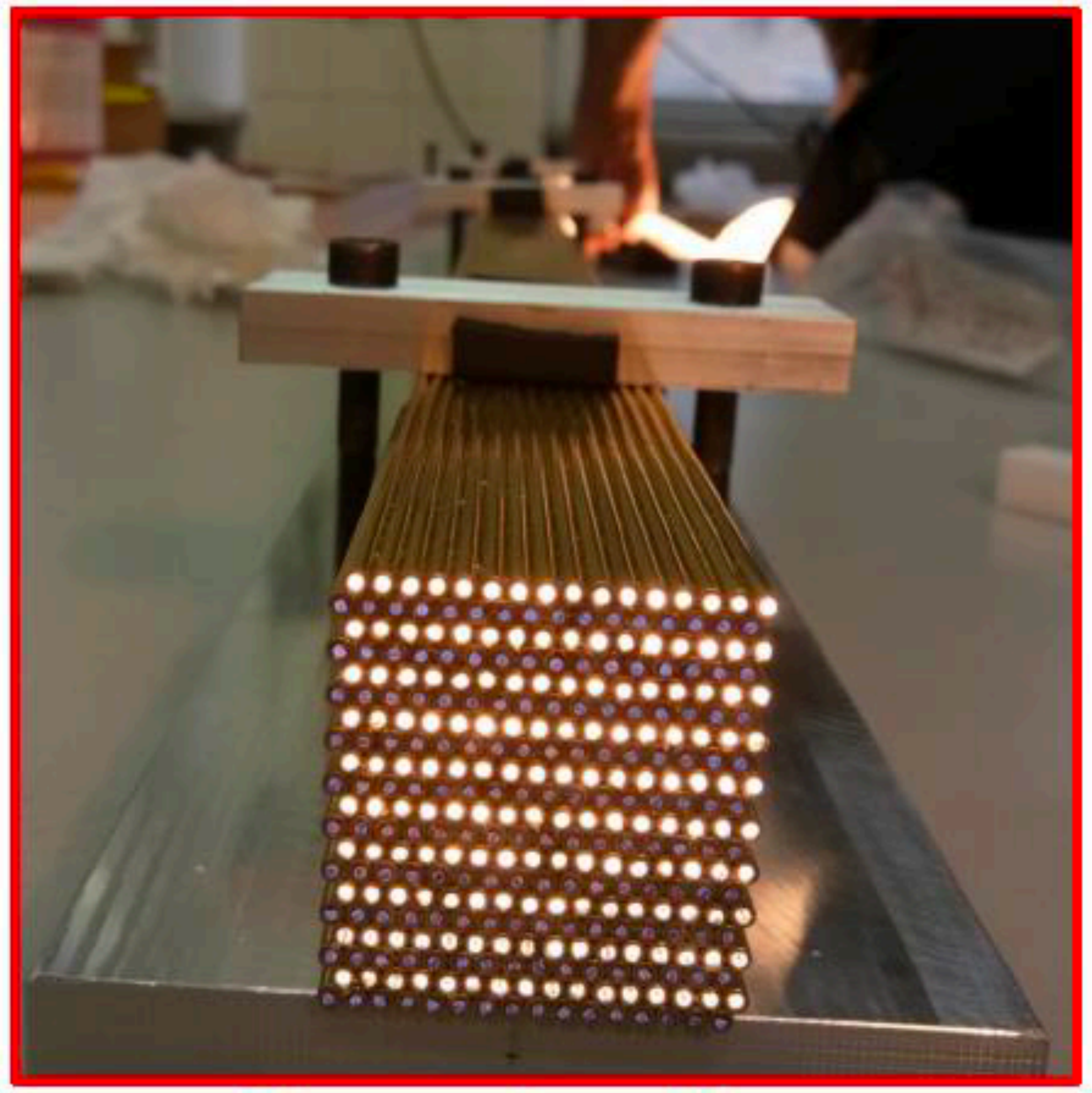
$$S = E[f_{em} + (h/e)_S(1 - f_{em})]$$

$$C = E[f_{em} + (h/e)_C(1 - f_{em})]$$

$$E = \frac{S - \chi C}{1 - \chi} \quad \text{with: } \chi = \frac{1 - (h/e)_S}{1 - (h/e)_C}$$

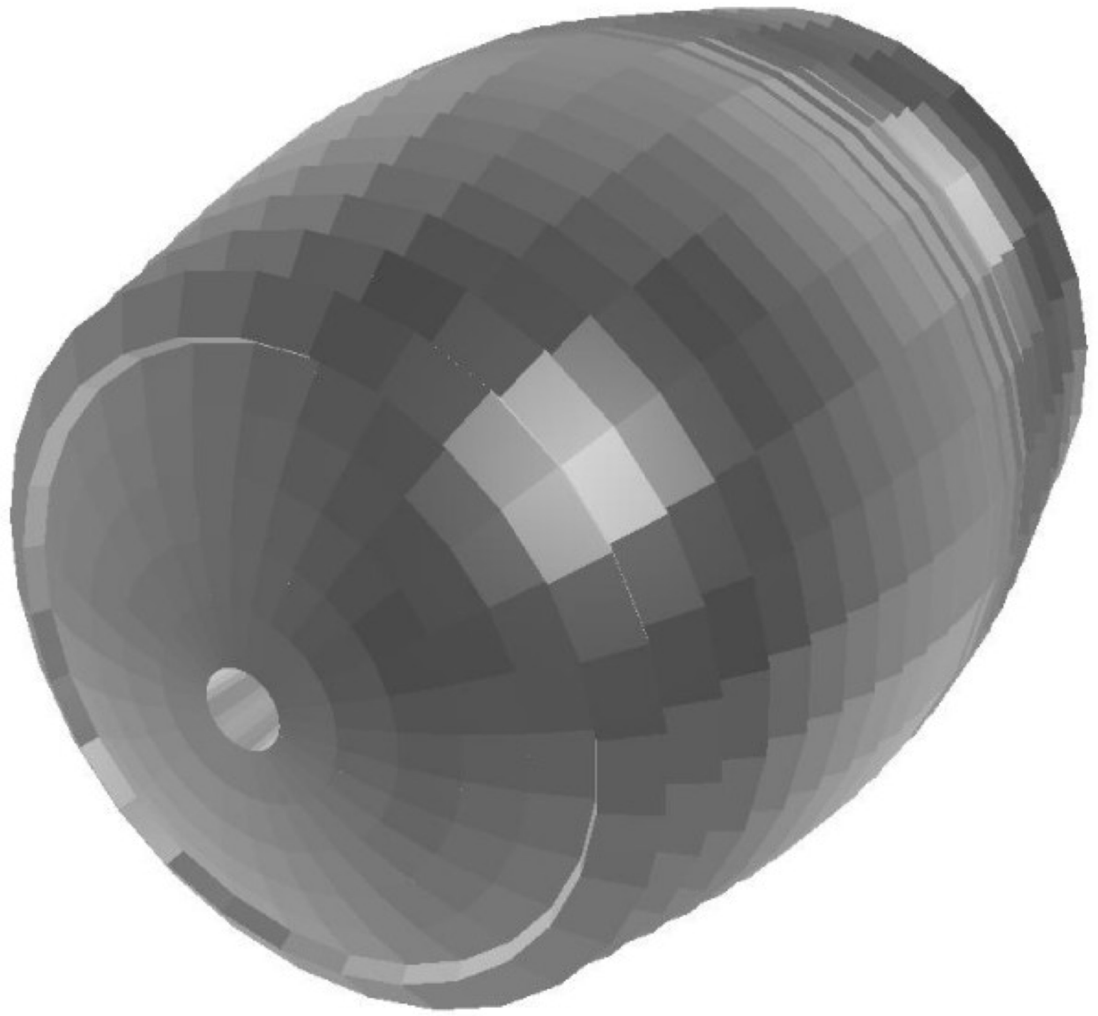
Newer DR calorimeter layout
(bucatini calorimeter)

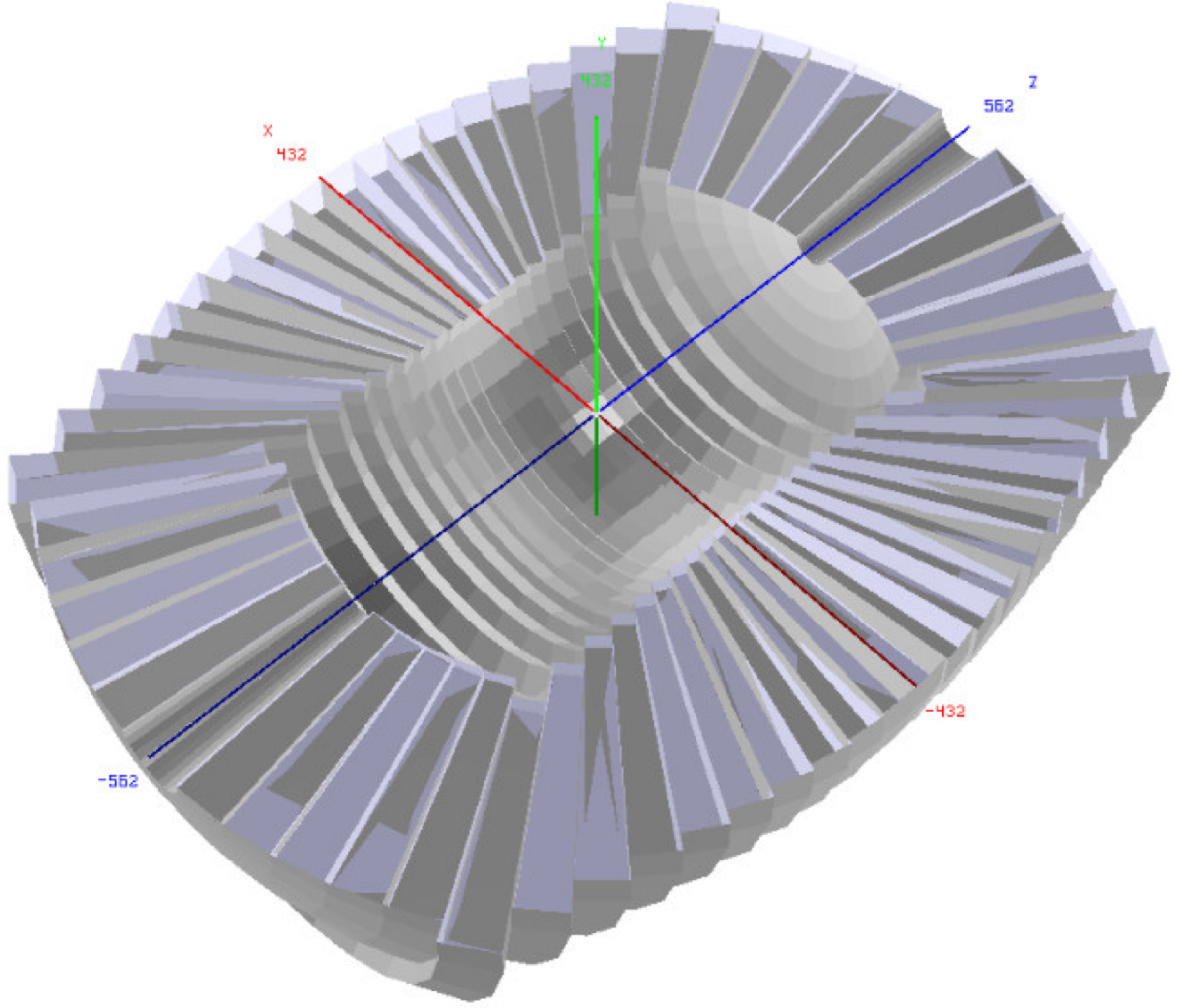
Scintillation fibers



Cherenkov fibers

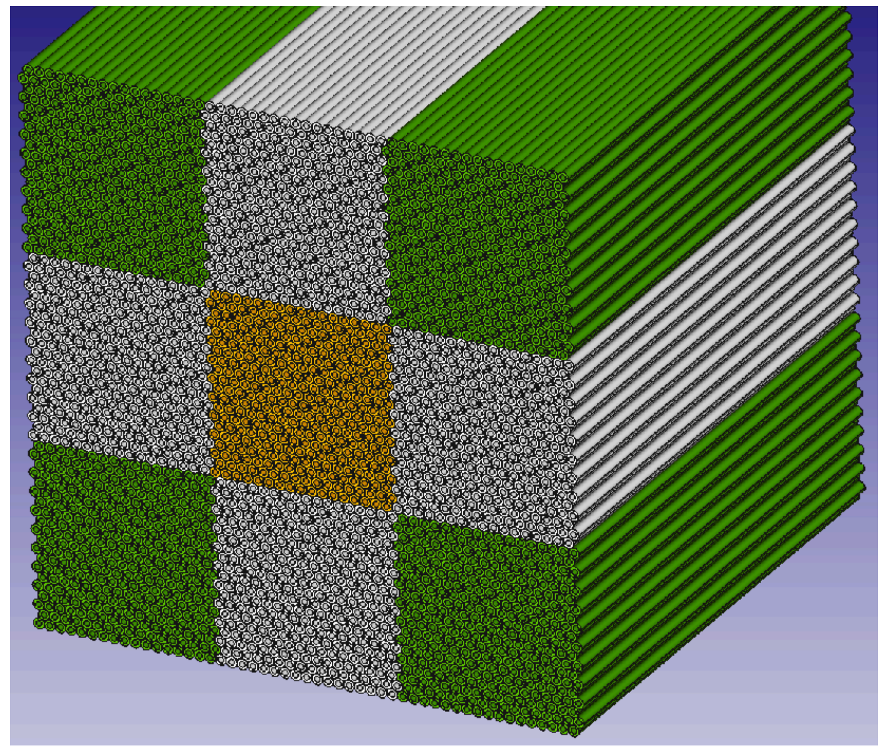
DUAL READOUT CALORIMETER SIMULATION



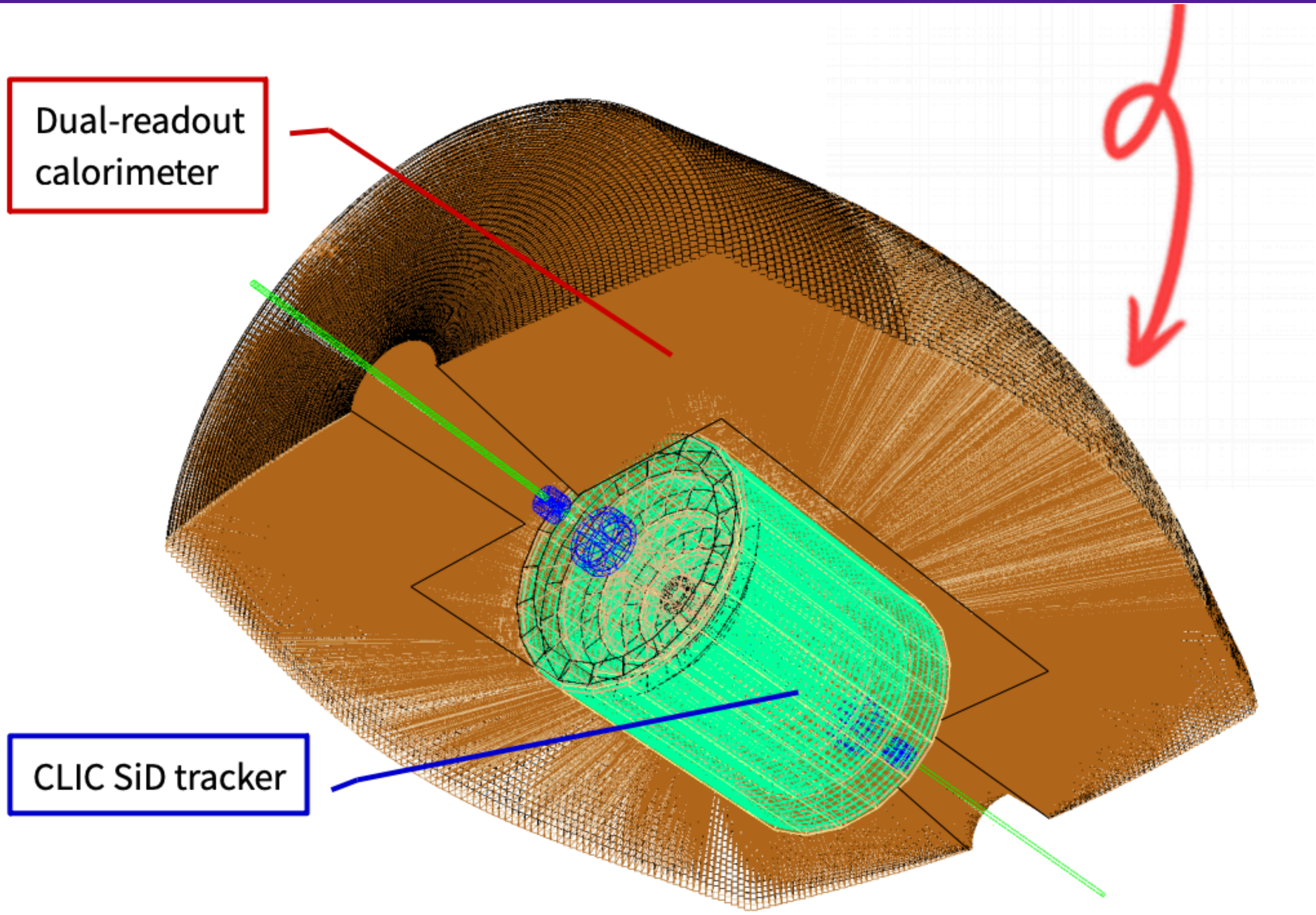


Tower segmentation: $\Delta\vartheta = 1.125°$, $\Delta\phi = 10.0°$
Number of towers in barrel: 40 x 2 x 36 = 2880
Number of towers per endcap: 35 x 36 = 1260
Theta coverage up to ~0.100 rad

Geant4 Geometry



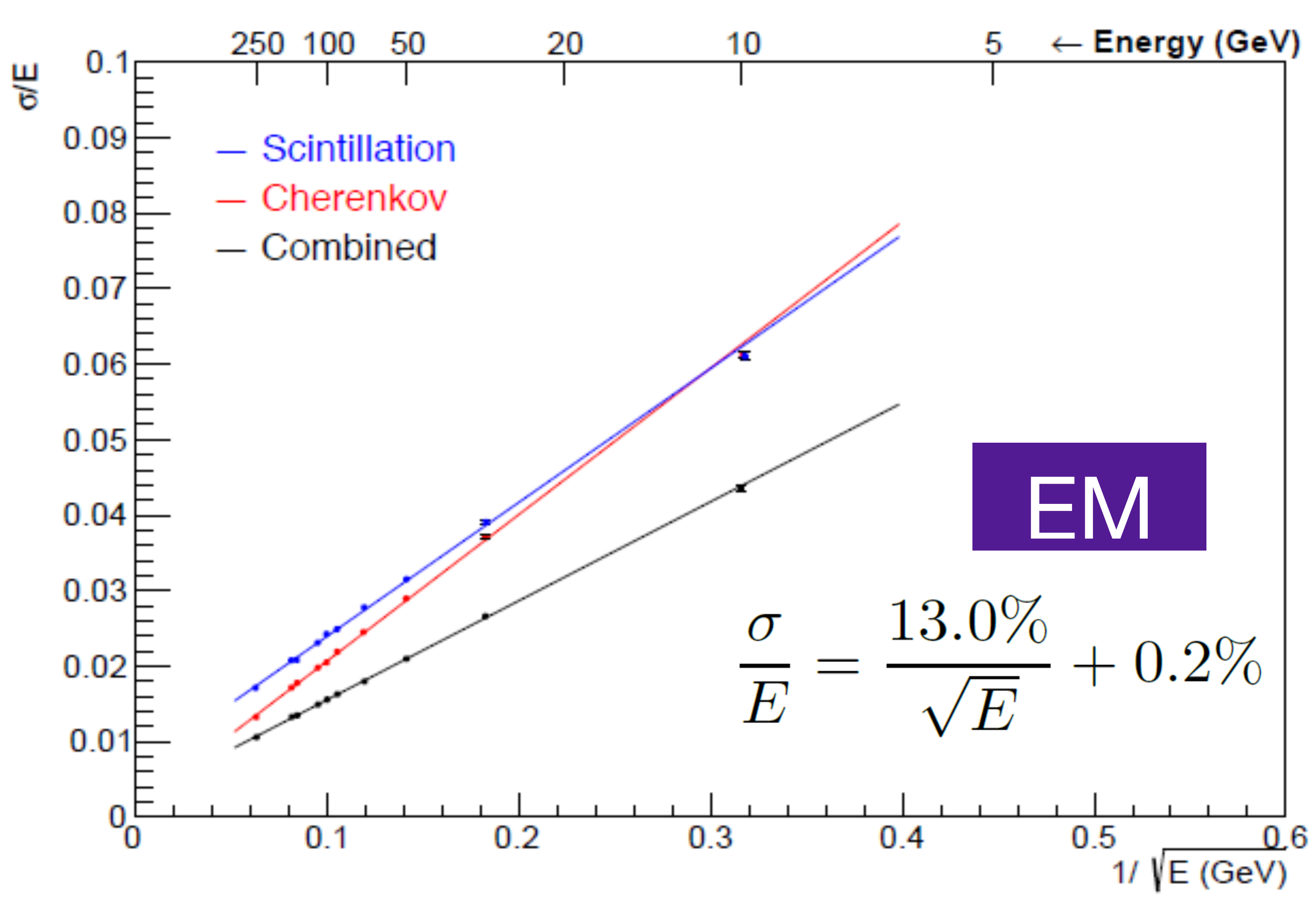
- **4π detector FullSimulation (G4) tuned to RD52 test beam data**

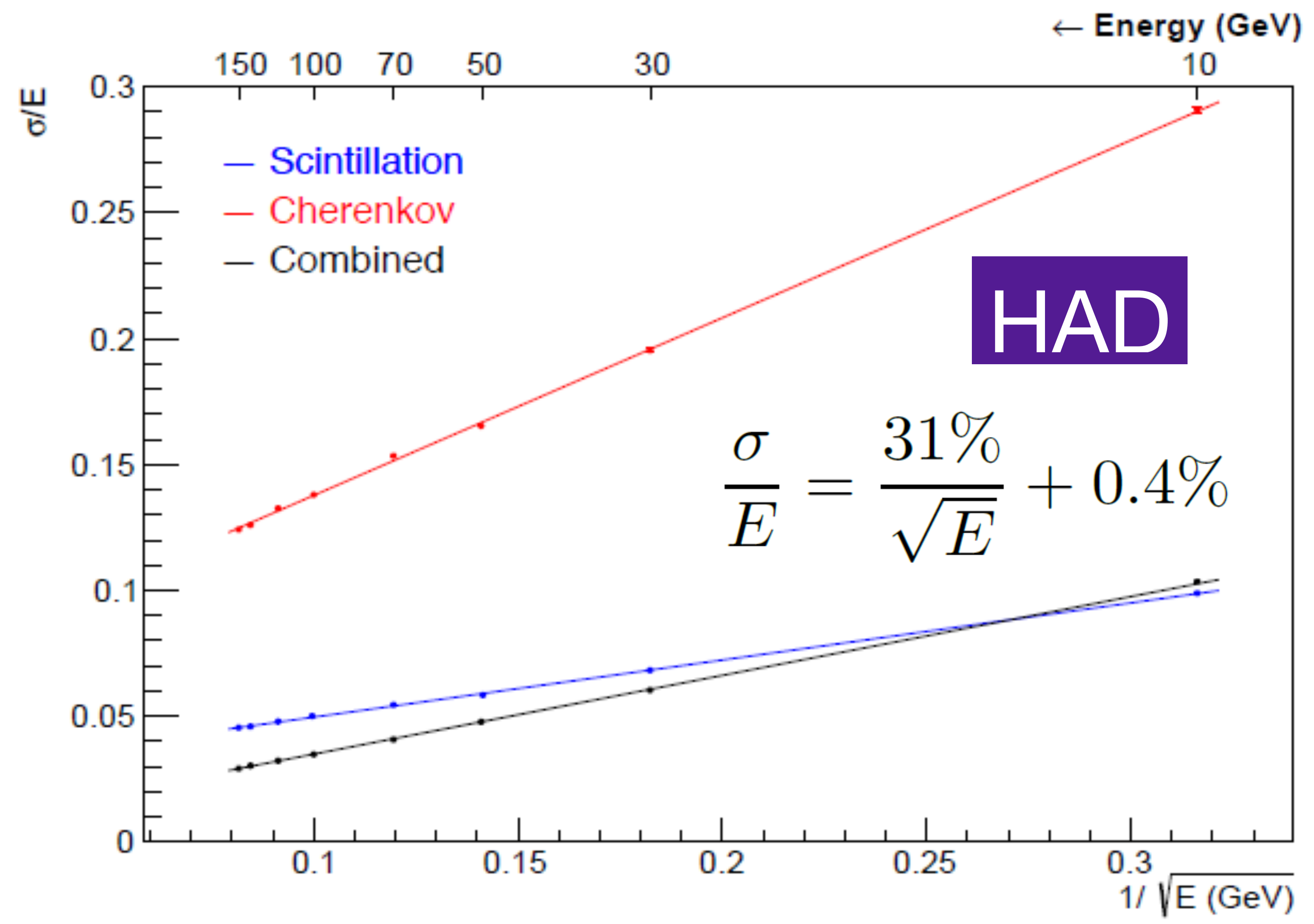


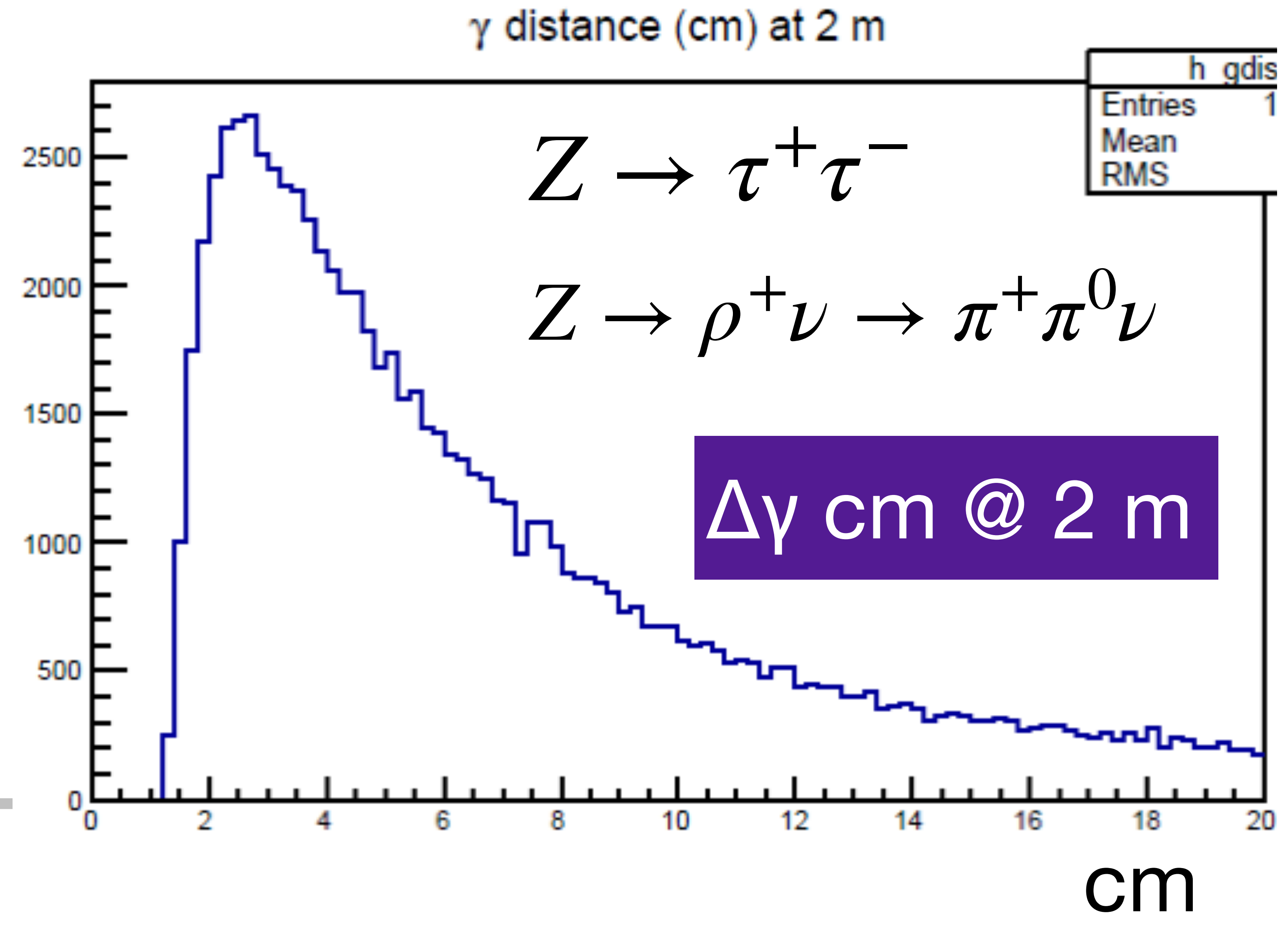
DD4HEP geometry: allows "plug&play" of different components: here the DR is paired with the CLD silicon tracker

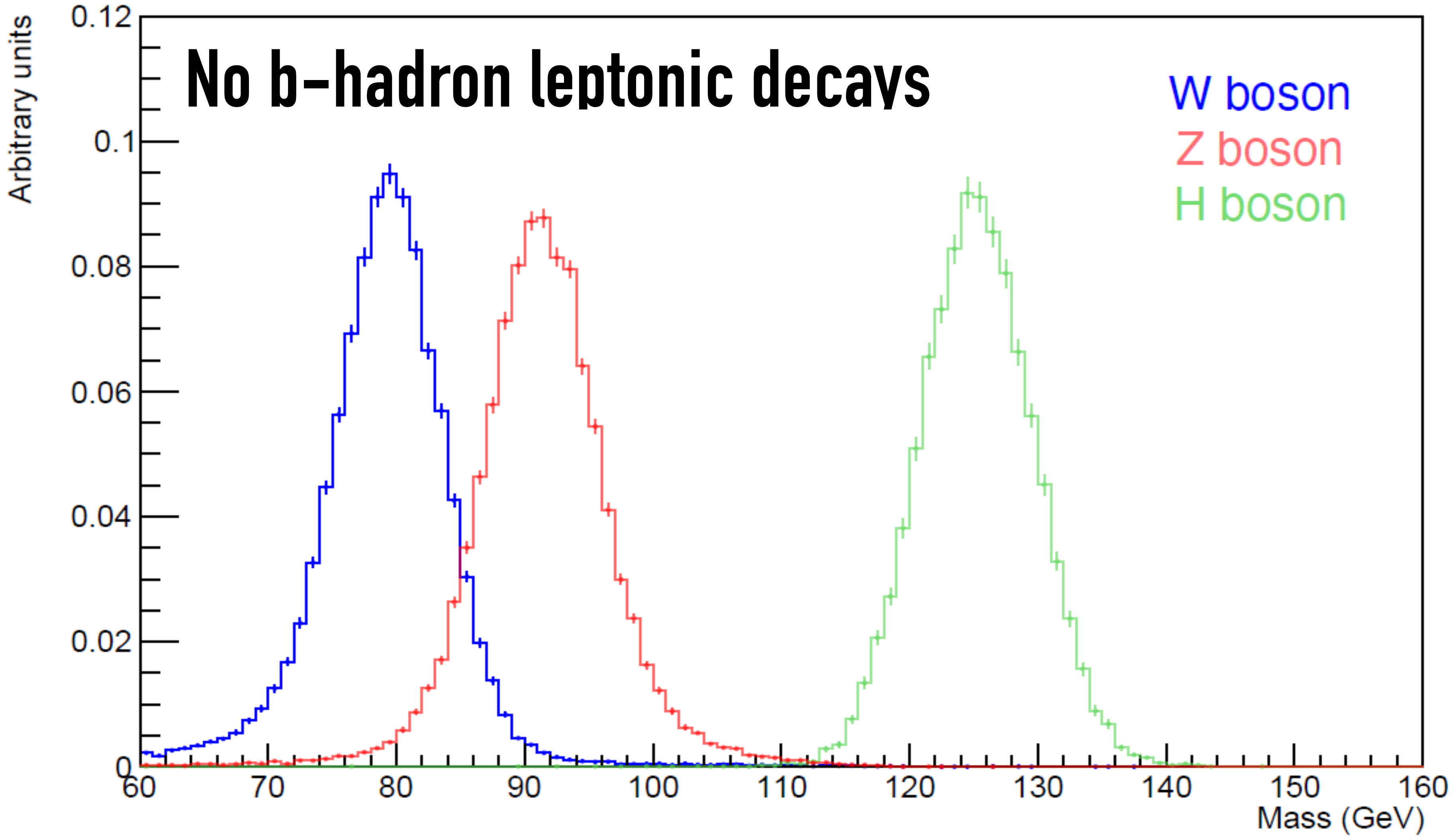
DR CALORIMETER PERFORMANCE

- **Good resolution averaged over η and ϕ**
- **Jet resolution:**
  - **~30-40%/$\sqrt{E}$ separates W, Z, H in 2-jet decays**
- **EM resolution:**
  - **~ 10-15%/$\sqrt{E}$ ok for Higgs physics**
  - **~3% more appropriate for HF**
- Transverse granularity <1cm for π^0 from τ and Heavy Flavor
- All electronics in the back to simplify cooling and services
- Ultimate angular resolution using single fibre …









Particle Flow reconstruction in DR with ML is being developed

patriz

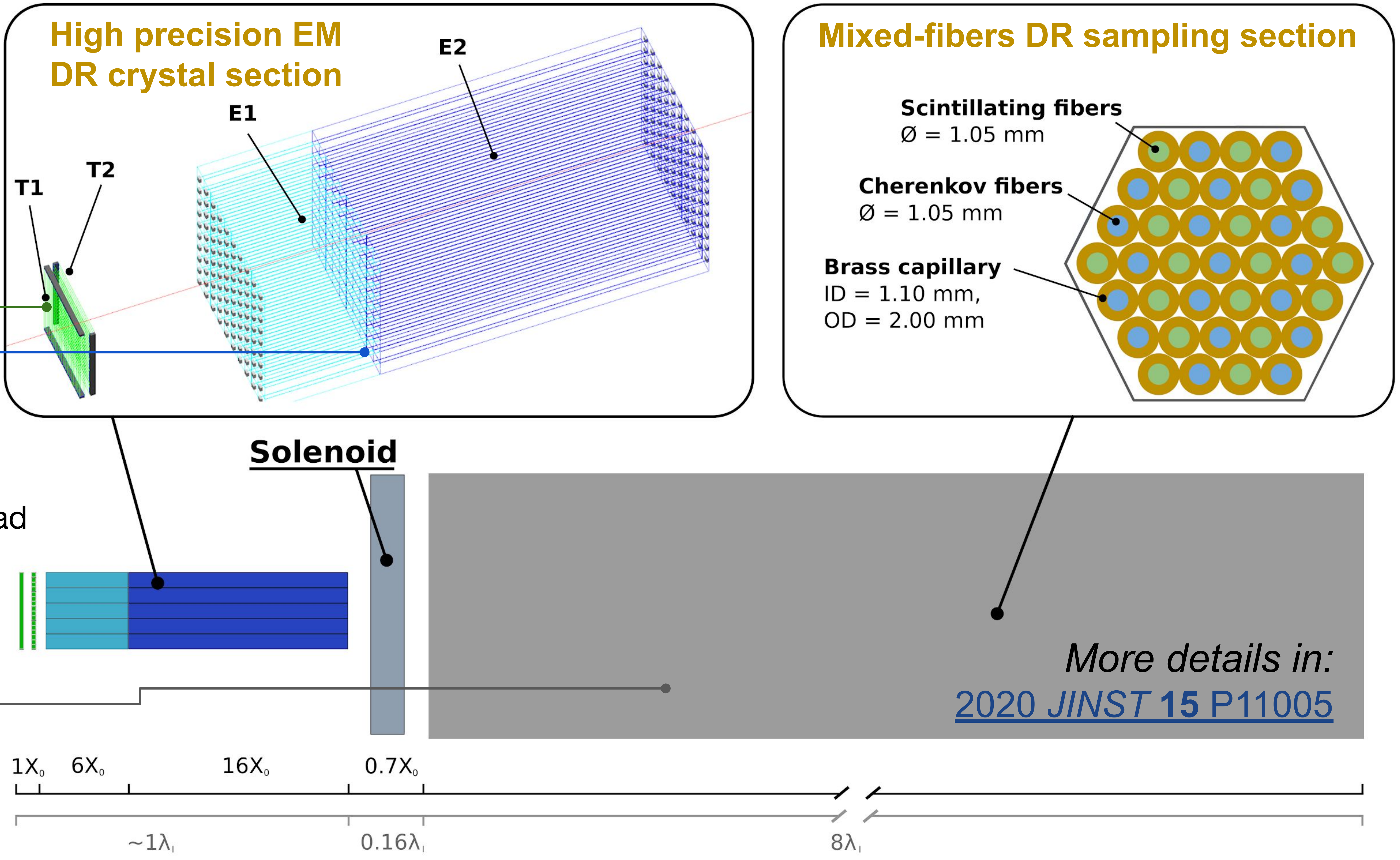
CRYSTAL ECAL OPTION CONCEPTUAL LAYOUT

See talk by Wonyong Paul Chung

- **Transverse and longitudinal segmentation** optimized for particle identification and particle flow algorithms
- Exploiting **SiPM readout** for contained cost and power budget

- **Timing layers** — $\sigma_t \sim 20$ ps
  - LYSO:Ce crystals ($\sim 1X_0$)
  - 3x3x60 mm³ active cell
  - 3x3 mm² SiPMs (15-20 um)
- **ECAL layers** — $\sigma^{EM}_E/E \sim 3\%/\sqrt{E}$
  - PWO crystals
  - Front segment ($\sim 6X_0$)
  - Rear segment ($\sim 16X_0$)
  - 10x10x200 mm³ crystal
  - 5x5 mm² SiPMs (10-15 um)

  angular resolution $\sigma\theta = 1.56/\sqrt{E} \oplus 0.33$ mrad
- **Ultra-thin IDEA solenoid**
  - $\sim 0.7X_0$
- **HCAL layer** — $\sigma^{HAD}_E/E \sim 26\%/\sqrt{E}$
  - Scintillating and "clear" PMMA fibers (for Cherenkov signal) inserted inside brass capillaries



More details in: 2020 *JINST* **15** P11005

EM CRYSTAL OPTION PERFORMANCE

FCC

Including the neutral decays in the reconstruction drives the ECAL resolution

2107.02002

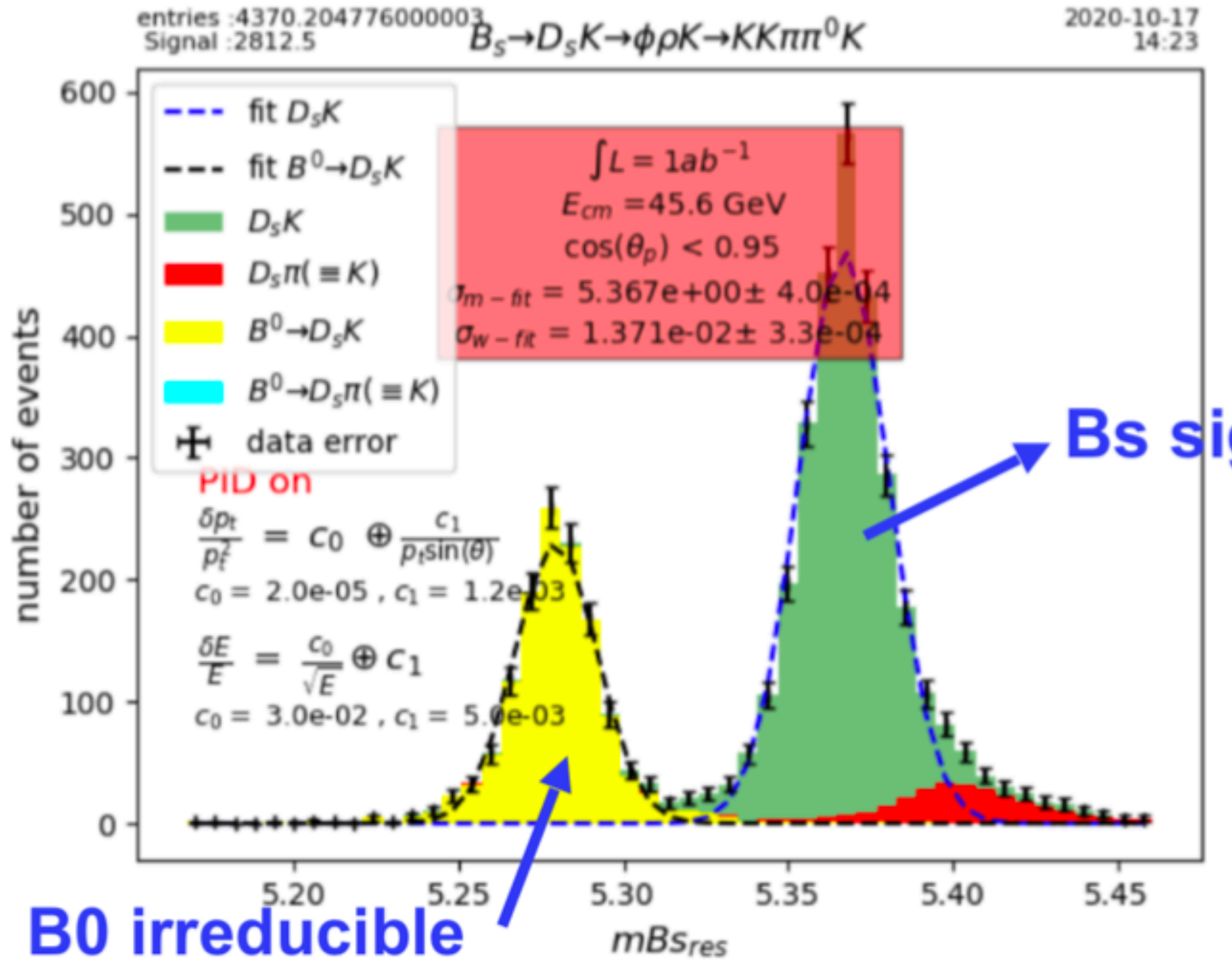
$D_s^+K^-$	$D_s^+ \to \phi\pi$	$K^+K^-\pi^+K^-$	$\sim 5.2\ 10^5$
$D_s^+K^-$	$D_s^+ \to \phi\rho$	$K^+K^-\pi^+K^-\pi^0$	$\sim 9.8\ 10^5$

Assuming **state-of-the-art** calorimeter with

$$\frac{\delta E}{E} = \frac{0.03}{\sqrt{E}} \oplus 0.005$$

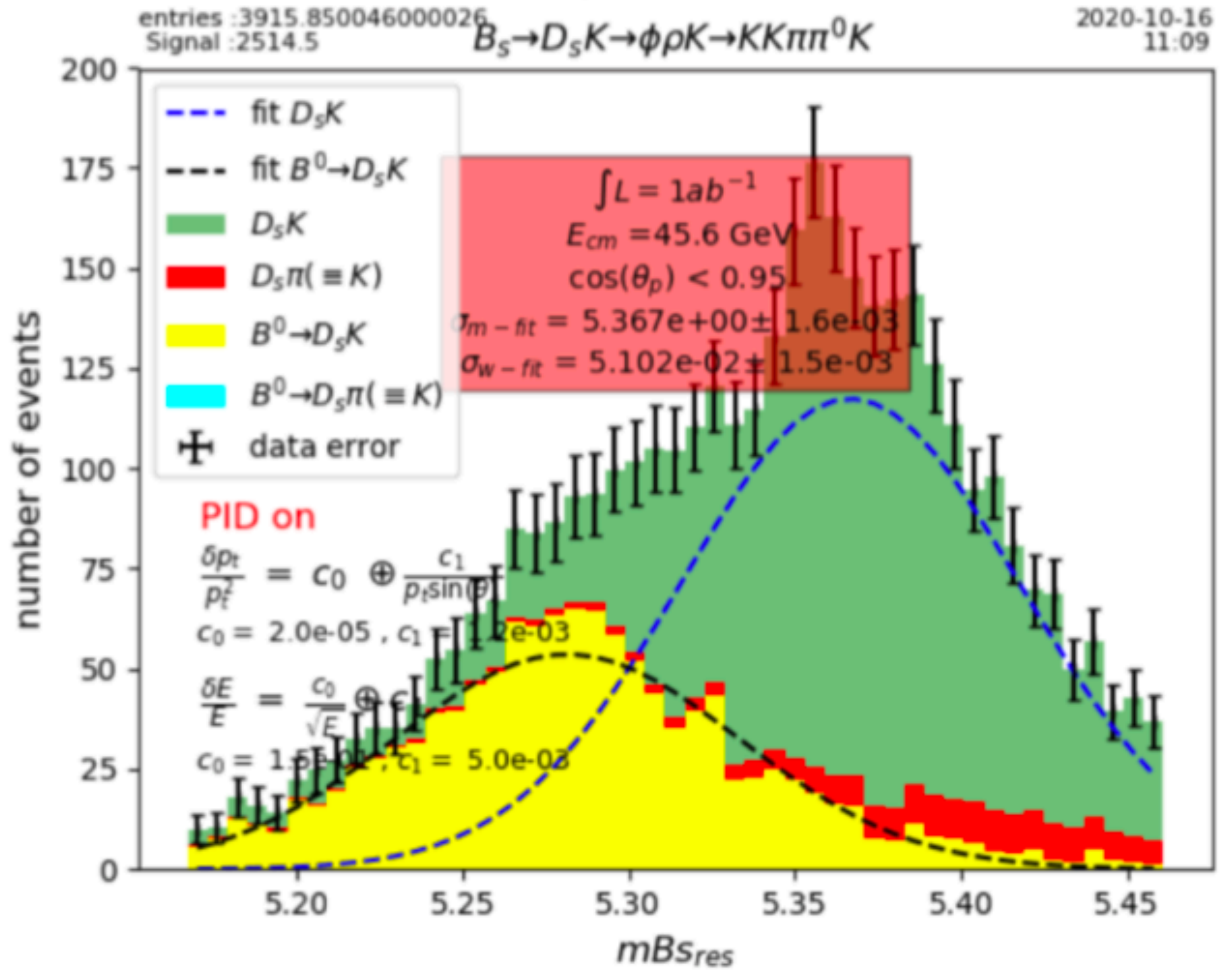
Assuming **HGCal like** calorimeter with

$$\frac{\delta E}{E} = \frac{0.15}{\sqrt{E}} \oplus 0.005$$

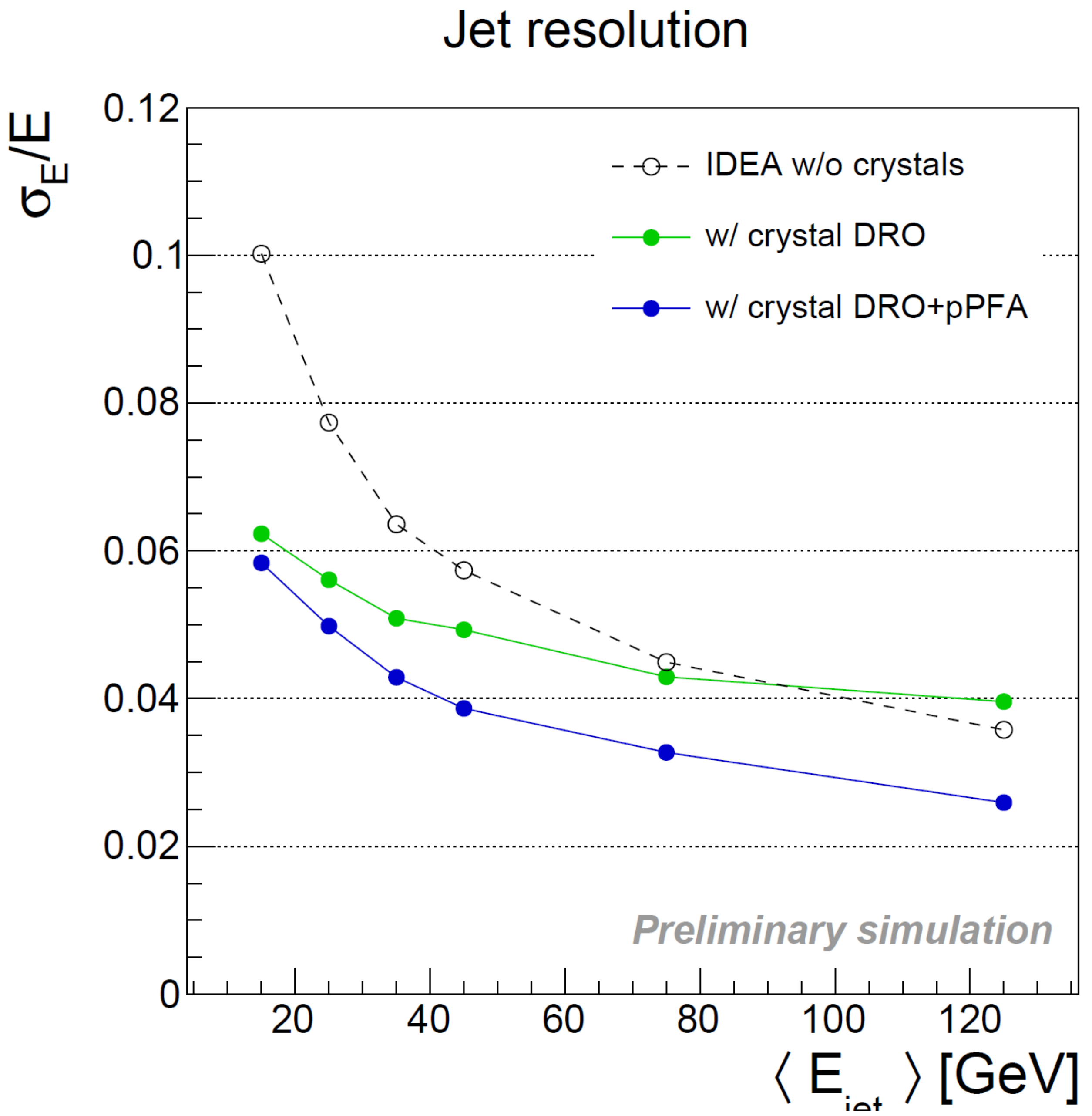


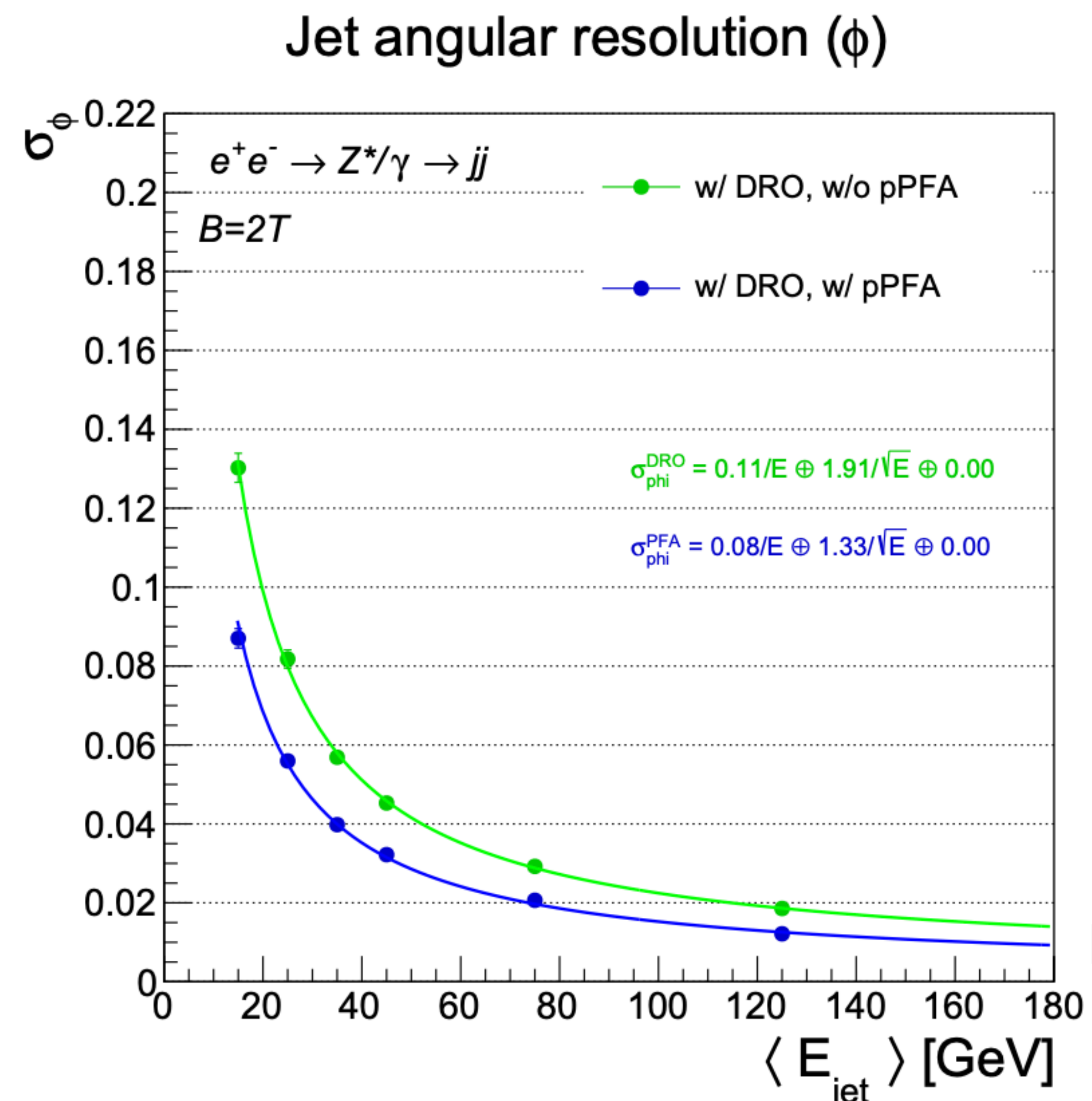
Bs signal

B0 irreducible bckgd



State-of-the-art Xtal-type to HGCal-type : $\sigma(D_s^\pm(\phi\rho^\pm)K^\mp) \approx 14MeV \to 51MeV$





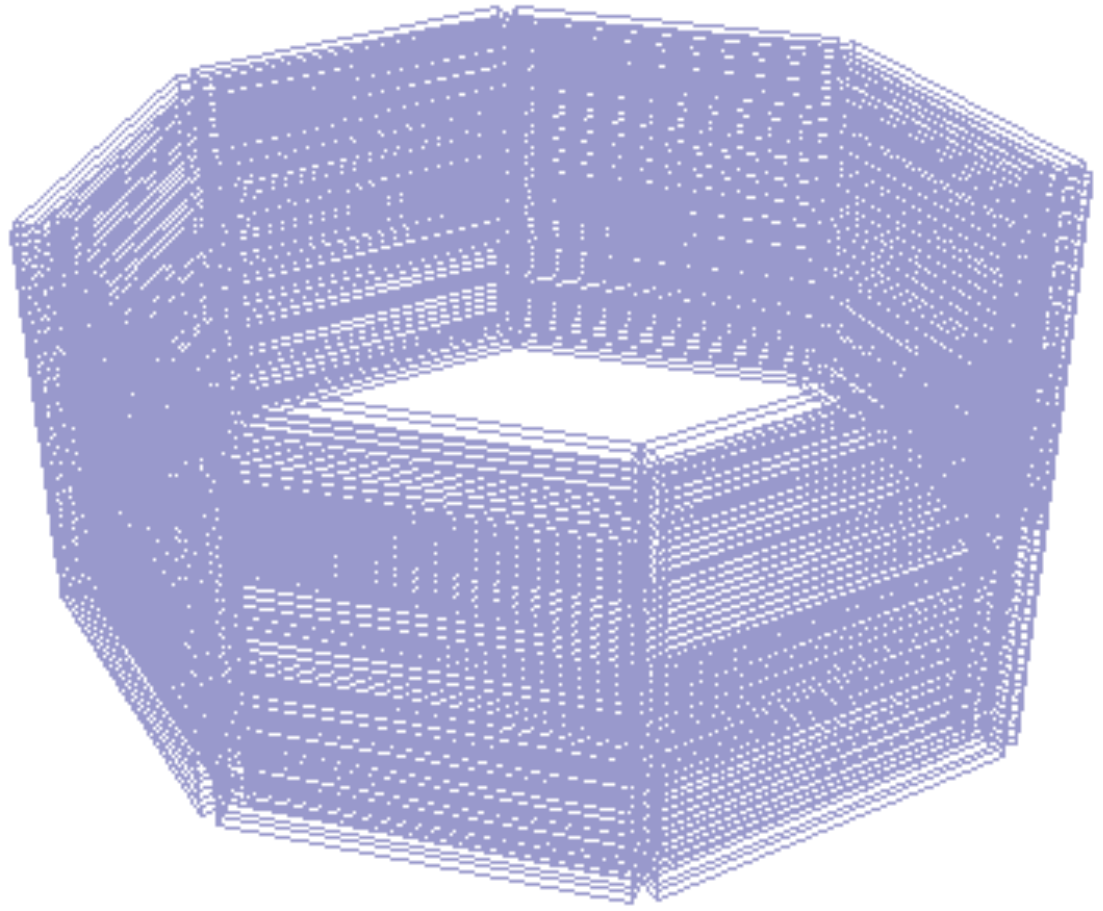
0.01mrad

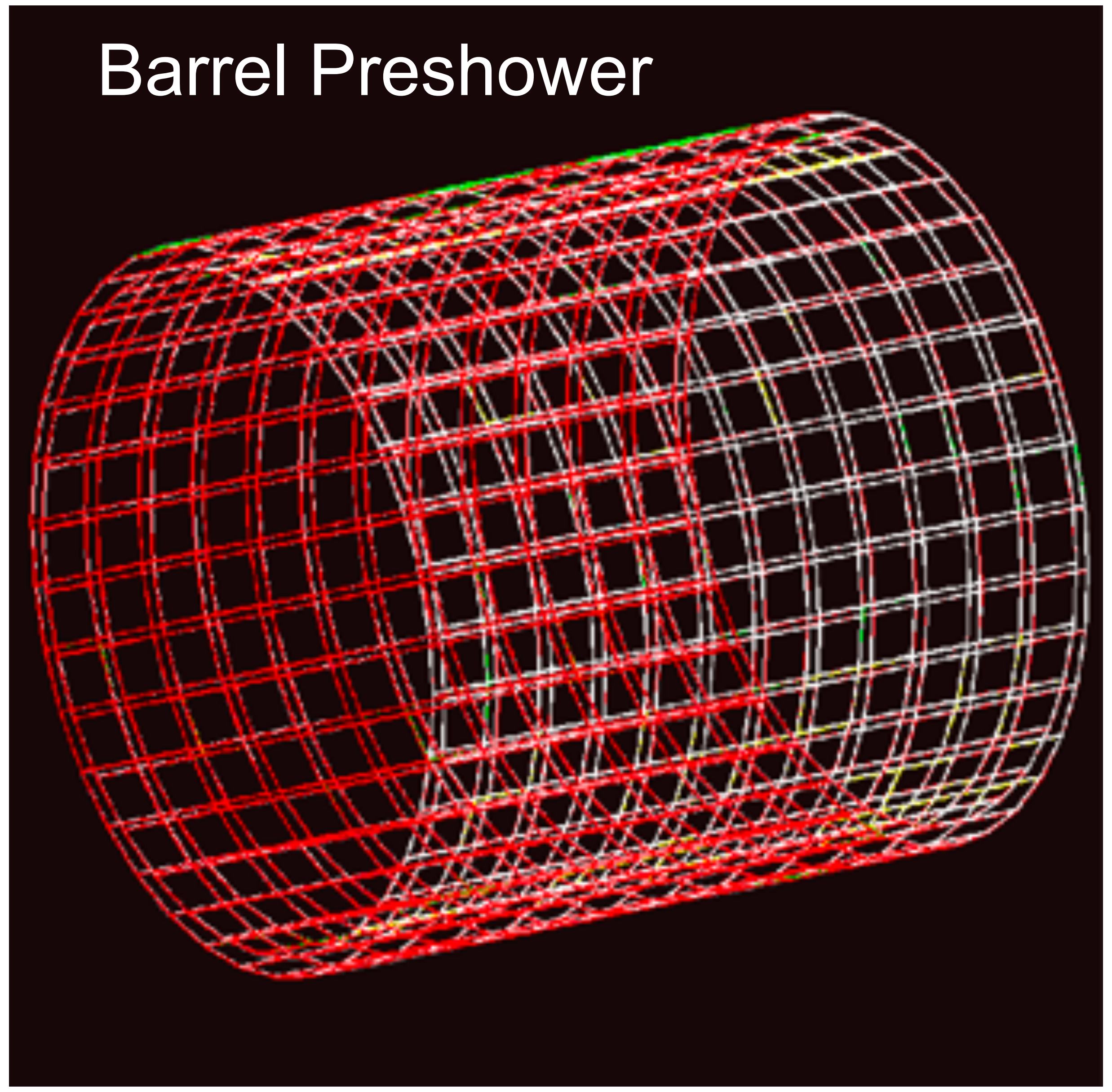
- **Improved EM energy resolution very important for jets and flavour/taus**
- **EM granularity also very important for flavor/taus and BSM physics to distinguish close-by photons**

MUON DETECTORS

- **Proposing to use a μ-RWELL* technology**
  - Concept proved and synergetic with LHC
  - Mass production/Optimization of FEE channels/cost
  - Efficiency > 98% & Space Resolution < 400 μm
- **Muon Detector:**
  - 50x50 cm2 2D tiles to cover more than 4330 m^2, Muon
  - pitch = 1.5 mm, FEE capacitance = 270 pF, 5M channels
- **Pre-Shower:**
  - pitch = 0.4 mm, FEE capacitance = 70 pF, 1.5M channels
  - High spatial resolution between magnet and calorimeter
  - Full Simulation description in progress

Barrel Muon





(*) G. Bencivenni et al., "The micro-Resistive WELL detector: a compact spark-protected single amplification-stage MPGD", 2015_JINST_10_P02008)

INFN FCC DETECTOR R&D EFFORTS

- **Structured detector R&D efforts with additional contributions from funds outside INFN and/or synergies:**
  - Tracking detectors
    - **Vertex pixel detector: ARCADIA**
    - **Silicon wrapper: AtlasPix3 – International collaboration**
    - **Drift chamber design and cluster counting study**
      - Synergy with MEG2 chamber and Tau-charm factory R&D
    - **Muon chambers: µRwell technology – synergy with LHCb upgrades**
  - Calorimeter
    - **DR calo new mechanical & electronics solutions – Digital SiPMs and full containment prototype - International collaboration**
    - **ECAL Crystal - International collaboration (Calvision)**
  - Many contributions in European projects such as AIDAInnova and ECFA DRDs

FINAL COMMENTS

- **IDEA represent the effort to develop a new detector concept for FCC-ee able to fully exploit it's physics potential**
  - with particular attention on the new opportunities offered by the Tera-Z program for flavour and BSM
- **INFN has setup a complete R&D effort but resources for future projects are limited**
    - **People are involved in running/approved experiments and can devote only a small fraction of time**
  - Additional collaborators are welcome in all areas: from hardware R&D to software
  - Many new ideas waiting to be pursued further or not really explored yet
    - **Current IDEA description is a baseline that should evolve**
- **Expanding our international collaboration is our goal**
  - Open to synergies with the US community on this and other detector concepts

BACKUP

FCC-ee PHYSICS PROGRAMME WITH 2 IPs AND 15 YEARS

➤ **Arguably enough physics for 4 IPs (and for a longer time, if needed)**

FCC-ee

1 "intensity frontier"

FCC-ee: 6 yrs

EW & QCD

- m_Z, Γ_Z, N_ν
- R_l, A_{FB}
- m_W, Γ_W
- $\alpha_s(m_Z)$ with per-mil accuracy
- Quark and gluon fragmentation
- Clean non-perturbative QCD studies

Detector req.: particle flow, energy resol., particle ID

direct searches of light new physics

- Axion-like particles, dark photons, Heavy Neutral Leptons
- long lifetimes - LLPs

Detector req.: detector hermeticity, tracking, calorimetry

Rare/forbidden decays

flavour factory
(10^{12} bb/cc; $1.7\text{x}10^{11}$ $\tau\tau$)

τ physics

- τ-based EWPOs
- lept. univ. violation tests

Detector req.: momentum resol., tracker

B physics

- Flavour EWPOs (R_b, $A_{FB}^{b,c}$)
- CKM matrix,
- CP violation in neutral B mesons
- Flavour anomalies in, e.g., $b \to s\tau\tau$

Detector req.: vertexing, tagging, energy resolution, hadron identification

detector req.

Programme optimally done with circular collider's first stage

2 Higgs

Programme also accessible to linear collider's first stage

- m_{Higgs}, Γ_{Higgs}
- Higgs couplings
- self-coupling

ILC_{240}	11 yrs
$CLIC_{380}$	8 yrs
FCC-ee:	3 yrs

3 Top

- m_{top}, Γ_{top}
- EW top couplings

$CLIC_{380}$	
FCC-ee:	5 yrs

Programme also accessible to linear collider's first stage

Slide from C. Grojean @ FCC Week'22

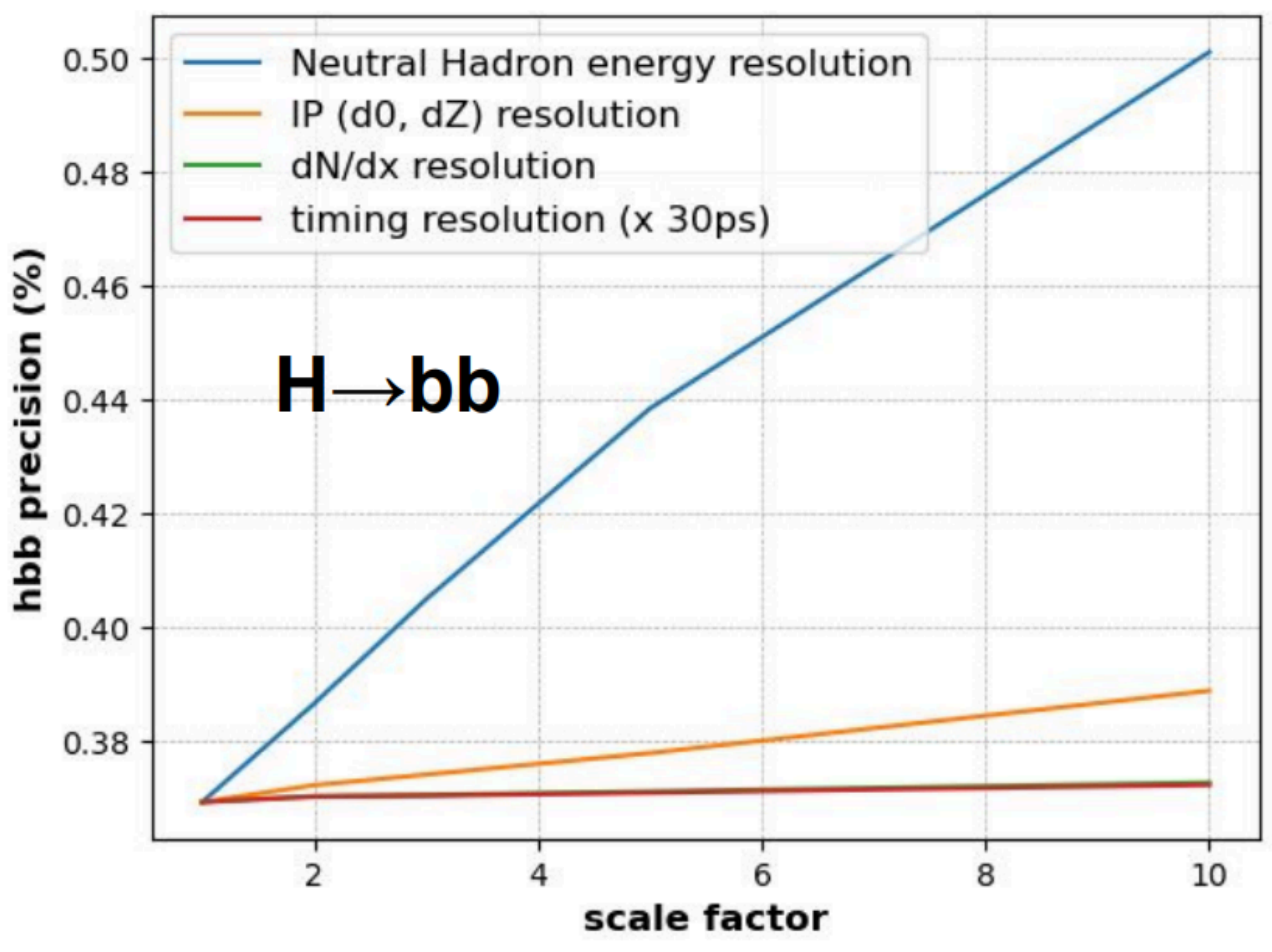
SOME DIFFERENCES WITH ILC/CLIC

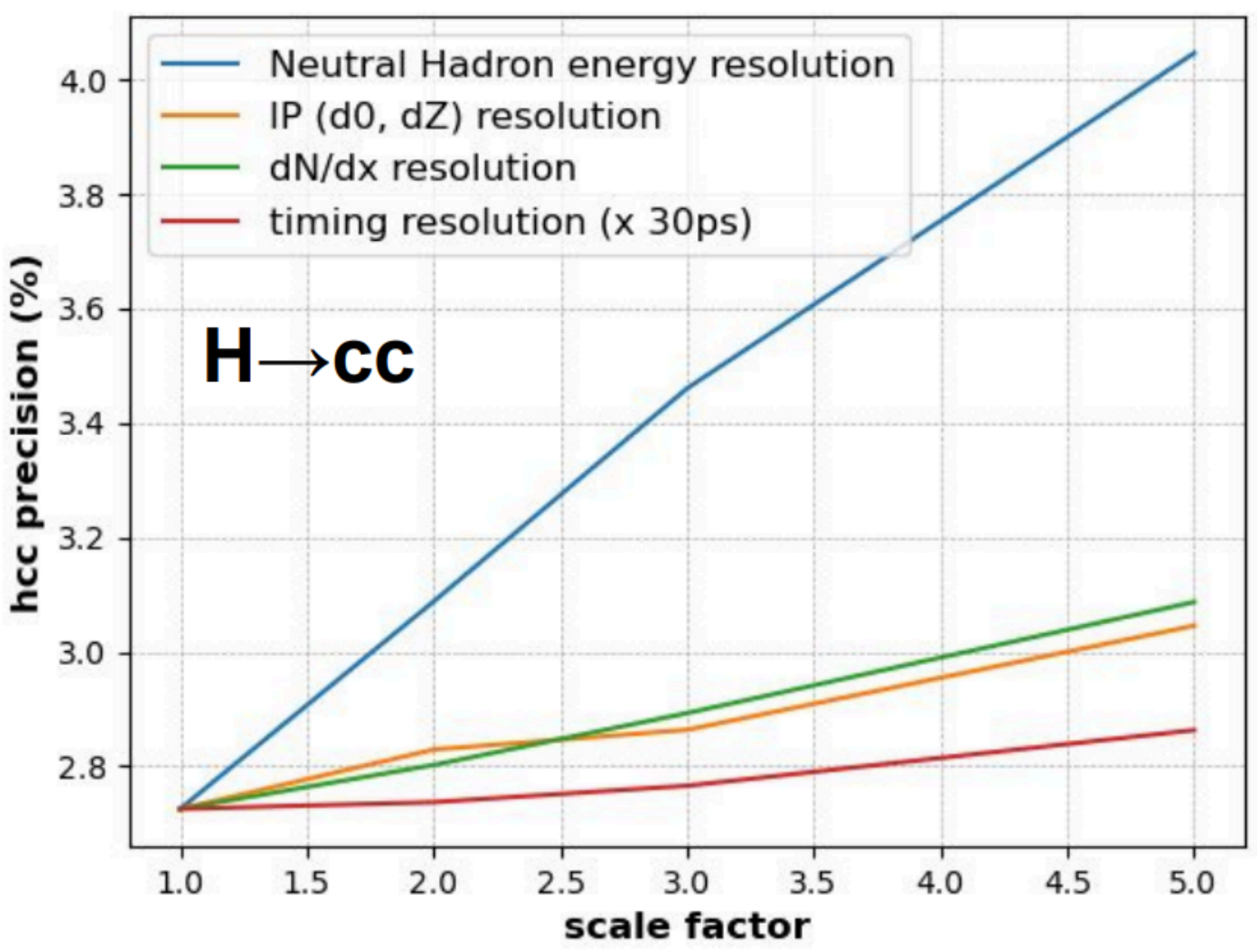
- **Different beam time structure:**
  - Short bunch spacing (~20 ns @Z, ~1 μs @H, ~ 3 μs @$t\bar{t}$)
  - No large time gap
    - **Cooling issues for PF calorimeter and vertex detector**
    - **TPC ion backflow**
- **Detector solenoid field strength constrained by beam emittance preservation at IR (~ 2T preferable)**
  - TPC: issues with transverse diffusion
  - Silicon: can't compensate smaller tracking radius with large field
- **Luminosity is much higher**
  - Non-negligible machine backgrounds
    - **Fast detector integrates less background in each readout**

Detector performance impact

- Last meeting: only showed Hadronic resolution and IP
  - Today also time-of-flight and dNdx
- Neutral Hadron resolution (affects m_{jj}, m_{recoil})
- Impact parameter resolution (affects tagger performance)

Caveat: IP variations pessimistic (tagger not retrained)





5

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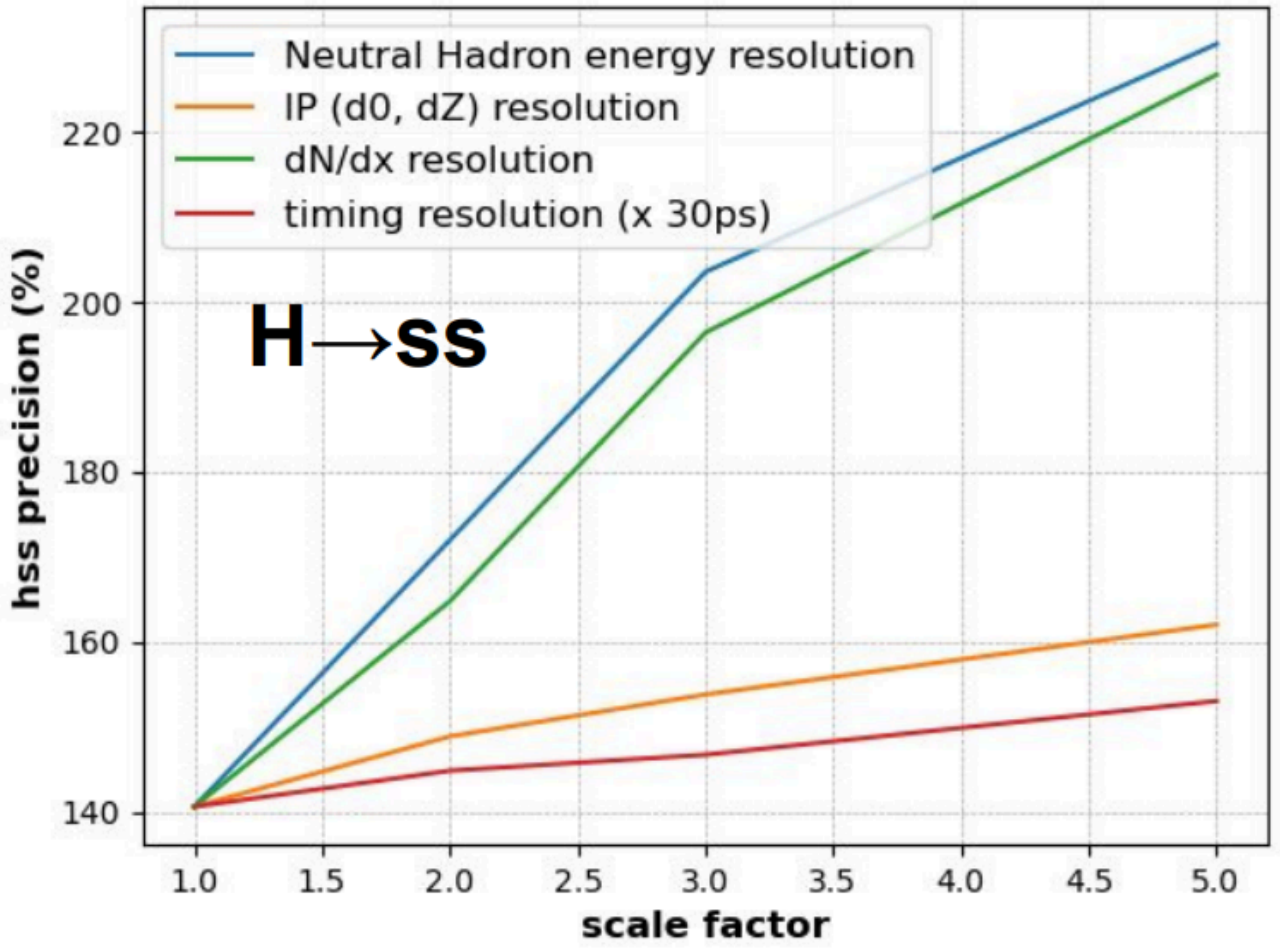

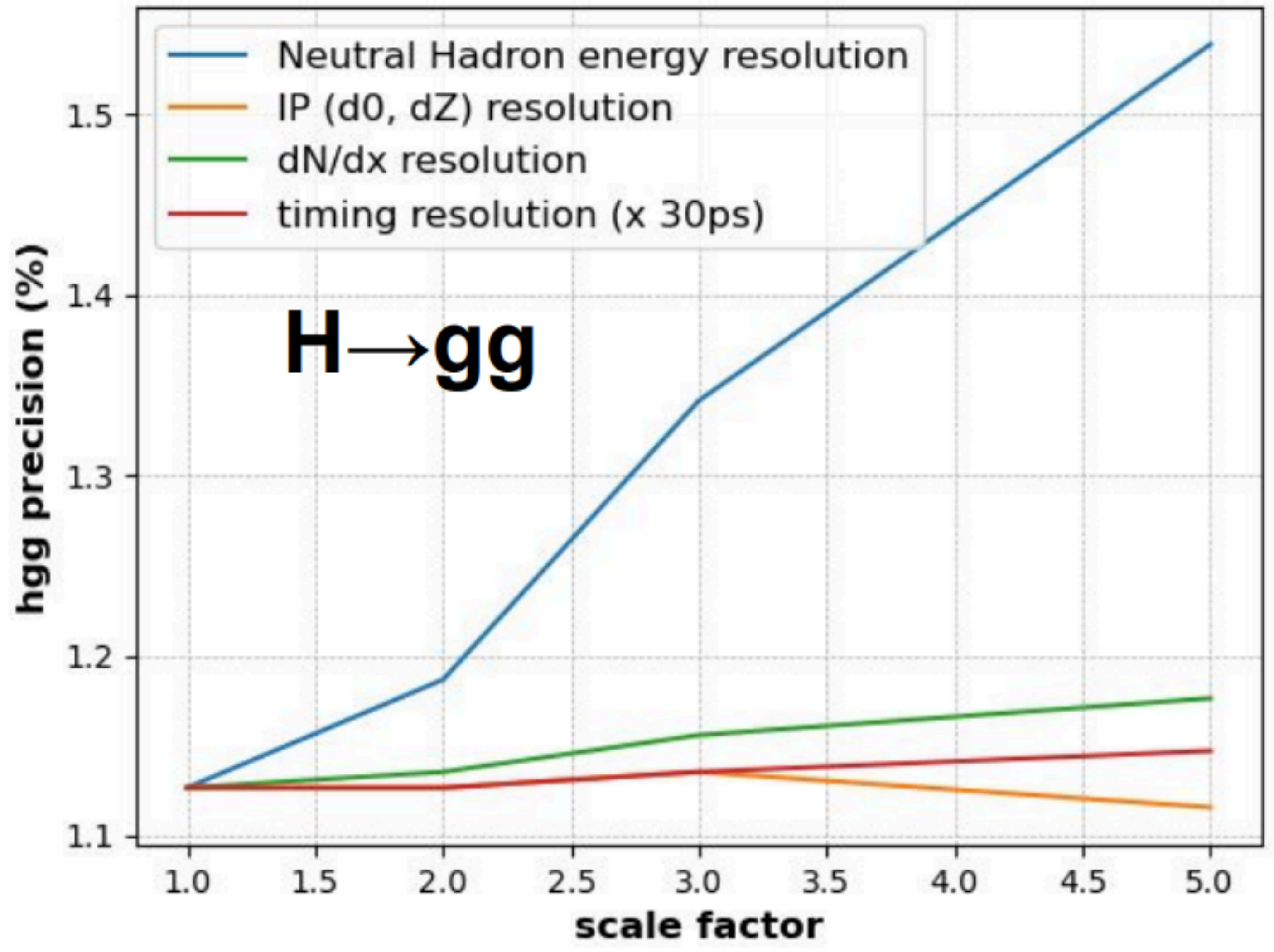

6